Rainfed Agriculture:

Unlocking the Potential

Comprehensive Assessment of Water Management in Agriculture Series

Titles Available

Volume 1. Water Productivity in Agriculture: Limits and Opportunities for Improvement
Edited by Jacob W. Kijne, Randolph Barker and David Molden

Volume 2. Environment and Livelihoods in Tropical Coastal Zones: Managing Agriculture–Fishery–Aquaculture Conflicts
Edited by Chu Thai Hoanh, To Phuc Tuong, John W. Gowing and Bill Hardy

Volume 3. The Agriculture Groundwater Revolution: Opportunities and Threats to Development
Edited by Mark Giordano and Karen G. Villholth

Volume 4. Irrigation Water Pricing: The Gap Between Theory and Practice
Edited by François Molle and Jeremy Berkoff

Volume 5. Community-based Water Law and Water Resource Management Reform in Developing Countries
Edited by Barbara van Koppen, Mark Giordano and John Butterworth

Volume 6. Conserving Land, Protecting Water
Edited by Deborah Bossio and Kim Geheb

Volume 7. Rainfed Agriculture: Unlocking the Potential
Edited by Suhas P. Wani, Johan Rockström and Theib Oweis

Rainfed Agriculture:

Unlocking the Potential

Edited by

Suhas P Wani
ICRISAT, India

Johan Rockström
SEI, Sweden

and

Theib Oweis
ICARDA, Syria

www.cabi.org

in association with

ICRISAT
Science with a human face

IWMI
International
Water Management
Institute

CABI is a trading name of CAB International

CABI Head Office
Nosworthy Way
Wallingford
Oxfordshire OX10 8DE
UK

Tel: +44 (0)1491 832111
Fax: +44 (0)1491 833508
E-mail: cabi@cabi.org
Website: www.cabi.org

CABI North American Office
875 Massachusetts Avenue
7th Floor
Cambridge, MA 02139
USA

Tel: +1 617 395 4056
Fax: +1 617 354 6875
E-mail: cabi-nao@cabi.org

A catalogue record for this book is available from the British Library, London, UK.

Library of Congress Cataloging-in-Publication Data

Rainfed agriculture : unlocking the potential / edited by Suhas P. Wani, Johan Rockström, and Theib Oweis.
p. cm. -- (Comprehensive assessment of water management in agriculture series ; 7)
Includes bibliographical references and index.
ISBN 978-1-84593-389-0 (alk. paper)
1. Dry farming--Asia. 2. Dry farming--Africa. 3. Water in agriculture--Asia. 4. Water in agriculture--Africa. 5. Watershed management--Asia. 6. Watershed management--Africa. I. Wani, S. P. II. Rockström, Johan. III. Oweis, Theib Yousef. IV. Series.

SB110.R325 2009

631.5′86--dc22 2008031275

ISBN-13: 978 1 84593 389 0

Typeset by Columns Design Ltd, Reading, UK.
Printed and bound in the UK by the MPG Books Group.

Contents

Contributors

P.K. Aggarwal, *Head of Division, Indian Agricultural Research Institute, New Delhi 110 012, India. Email: pkaggarwal.iari@gmail.com*

B. Benli, *International Center for Agricultural Research Institute in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria.*

V.S. Bhatia, *Crop Physiologist, National Research Centre for Soybean (NRCS), Khandwa Road, Indore 452 017, Madhya Pradesh, India. Email: Bhatia_virender-singh@hotmail.com*

T. Bhattacharyya, *Principal Scientist, Division of Soil Resource Studies, National Bureau of Soil Survey & Land Use Planning, Amravati Road, Nagpur 440 010, Maharashtra, India. Email: tapas11156@yahoo.com*

P. Chandran, *Division of Soil Resource Studies, National Bureau of Soil Survey & Land Use Planning, Amravati Road, Nagpur 440 010, Maharashtra, India.*

Y.S. Chauhan, *Plant Sciences, Department of Primary Industries and Fisheries, Kingaroy, Queensland, Australia (formerly with International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India). Email: yash.chauhan@dpi.qld.gov.au*

C. de Fraiture, *International Water Management Institute, PO Box 2075, Colombo, Sri Lanka. Email: c.fraiture@cgiar.org*

S.L. Dwivedi, *Visiting Scientist (Genetic Resources), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India. Email: s.dwivedi@cgiar.org*

M. Falkenmark, *Professor, Stockholm International Water Institute (SIWI), Drottninggatan 33, SE-111 51 Stockholm, Sweden. Email: malin.falkenmark@siwi.org*

R. Follkerstma, *De Ruiter Seeds Inc., Leeuwenhoekweg 52 2661, CZ, Bergschenhoek, the Netherlands. Email: sh936981@12move.nl*

P.M. Gaur, *Principal Scientist (Chickpea Breeding), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: p.gaur@cgiar.org*

C.L.L. Gowda, *Global Theme Leader, Crop Improvement, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: c.gowda@cgiar.org*

A. Hachum, *Consultant, Integrated Water and Land Management Program, International Center for Agricultural Research in the Dry Areas (ICARDA,) Aleppo, Syria.*

A.K. Jha, *Senior Research Associate, National Centre for Agricultural Economics and Policy Research (NCAP), Library Avenue, Pusa, New Delhi 110 01 (formerly with International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India). Email: akjha@ncap.res.in*

P.K. Joshi, *Director, National Centre for Agricultural Economics and Policy Research, Library Avenue, Pusa, New Delhi 110 012, India. Email: pkjoshi@ncap.res.in*

L. Karlberg, *Stockholm Environment Institute, Stockholm, Sweden. Email: louise.karlberg@sei.se*

P. Maniselvan, *Vegetable Breeder, BISCO Seeds India Pvt Ltd, India.*

M.V.R. Murty, *International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: murtymvr@rediffmail.com*

M. Nalini, *Senior Scientist, Cell Biology, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: n.mallikarjuna@cgiar.org*

S.N. Nigam, *Principal Scientist (Groundnut Breeding), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: s.nigam@cgiar.org*

J. Okello, *Department of Agricultural Economics, University of Nairobi, PO Box 29053, Nairobi 00625, Kenya. Email: okelloju@msu.edu*

T. Oweis, *Director, Integrated Water and Land Management Program, International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. Email: t.oweis@cgiar.org*

D.K. Pal, *Principal Scientist and Head, Division of Soil Resource Studies, National Bureau of Soil Survey & Land Use Planning, Amravati Road, Nagpur 440 010, Maharashtra, India. Email: dkpal@nbsslup.ernet.in*

M. Pala, *International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria.*

P. Pathak, *Principal Scientist (Soil & Water Management), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: p.pathak@cgiar.org*

H.K. Rai, *Assistant Professor, S K University of Agriculture & Technology, Srinagar, India. Email: h.rai@cgiar.org*

K.N. Rai, *Principal Scientist (Pearl Millet Breeding), Global Theme on Crop Improvement, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: k.rai@cgiar.org*

Y.S. Ramakrishna, *Director, Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad 500 059, Andhra Pradesh, India. Email: ramakrishna.ys@crida.ernet.in*

K.P.C. Rao, *International Center for Research on Agroforestry (ICRAF), Nairobi, Kenya. Email: k.p.c.rao@cgiar.org*

S.K. Ray, *Division of Soil Resource Studies, National Bureau of Soil Survey & Land Use Planning, Amravati Road, Nagpur 440 010, Maharashtra, India.*

B.V.S. Reddy, *Principal Scientist (Sorghum Breeding), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: b.reddy@cgiar.org*

L.J. Reddy, *D.No.46, ICRISAT Colony Phase I, Brg. Said Road, Secunderabad 500 009, India. Email:* LJ_REDDY@yahoo.com

V. Ratna Reddy, *Centre for Economics and Soil Studies (CESS), Nizamia Observatory Campus, Begumpet, Hyderabad 500 016, Andhra Pradesh, India. Email: vratnareddy@cess.ac.in*

J. Rockström, *Executive Director, Stockholm Environment Institute, Stockholm, Sweden. Email: johan.rockstrom@sei.se*

R.C. Sachan, *Visiting Scientist, Global Theme on Agroecosystems, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: r.sachan@cgiar.org*

K.L. Sahrawat, *Visiting Scientist (Soil Chemistry), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: k.sahrawat@cgiar.org*

R. Serraj, *Senior Scientist, Crop & Environmental Sciences Division, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines. Email: r.serraj@cgiar.org*

B. Shiferaw, *Principal Scientist and Program Leader (Markets, Institutions, Policies and Impacts), International Crops Research Institute for the Semi-Arid Tropics, PO Box 36063, Nairobi 00623, Kenya (formerly at ICRISAT, Patancheru 502 324, Andhra Pradesh, India). Email: b.shiferaw@cgiar.org*

P. Singh, *Principal Scientist (Soil Science), International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: p.singh@cgiar.org*

T.K. Sreedevi, *Scientist, Global Theme on Agroecosystems, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: t.sreedevi@cgiar.org*

G. Srinivasan, *Director AOU, University of California, Fresno, USA.*

R. Sudi, *Lead Scientific Officer, Global Theme on Agroecosystems, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: s.r.rao@cgiar.org*

H.D. Upadhyaya, *Principal Scientist, Genetic Resources, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: h.upadhyaya@cgiar.org*

S.P. Wani, *Principal Scientist (Watersheds) and Regional Theme Coordinator (Asia), Global Theme on Agroecosystems, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, Andhra Pradesh, India. Email: s.wani@cgiar.org*

P.H. Zaidi, *Scientist, Global Maize Program, CIMMYT's Asia Regional Office, Patancheru 502 324, Medak Dist., Andhra Pradesh, India. Email: phzaidi@cgiar.org*

Series Foreword: Comprehensive Assessment of Water Management in Agriculture

There is broad consensus on the need to improve water management and to invest in water for food as these are critical to meeting the Millennium Development Goals (MDGs). The role of water in food and livelihood security is a major issue of concern in the context of persistent poverty and continued environmental degradation. Although there is considerable knowledge on the issue of water management, an overarching picture on the water–food–livelihoods–environment nexus is missing, leaving uncertainties about management and investment decisions that will meet both food and environmental security objectives.

The Comprehensive Assessment of Water Management in Agriculture (CA) is an innovative, multi-institute process aimed at identifying existing knowledge and stimulating thought on ways to manage water resources to continue meeting the needs of both humans and ecosystems. The CA critically evaluates the benefits, costs and impacts of the past 50 years of water development and challenges to water management currently facing communities. It assesses innovative solutions and explores consequences of potential investment and management decisions. The CA is designed as a learning process, engaging networks of stakeholders to produce knowledge synthesis and methodologies. The main output of the CA is an assessment report that aims to guide investment and management decisions in the near future, considering their impact over the next 50 years in order to enhance food and environmental security to support the achievement of the MDGs. This assessment report is backed by CA research and knowledge-sharing activities.

The primary assessment research findings are presented in a series of books that form the scientific basis for the Comprehensive Assessment of Water Management in Agriculture. The books cover a range of vital topics in the areas of water, agriculture, food security and ecosystems – the entire spectrum of developing and managing water in agriculture, from fully irrigated to fully rainfed lands. They are about people and society, why they decide to adopt certain practices and not others and, in particular, how water management can help poor people. They are about ecosystems – how agriculture affects ecosystems, the goods and services ecosystems provide for food security and how water can be managed to meet both food and environmental security objectives. This is the seventh book in the series.

Effectively managing water to meet food and environmental objectives will require the concerted action of individuals from across several professions and disciplines – farmers, fishers, water managers, economists, hydrologists, irrigation specialists, agronomists and social scientists. The material presented in this book represents an effort to bring a diverse group of people together to present a truly cross-disciplinary perspective on rainfed agriculture. The complete set of books should be invaluable for resource managers, researchers and field implementers. These books will provide source material from which policy statements, practical manuals and educational and training material can be prepared.

The CA is done by a coalition of partners that includes 11 Future Harvest agricultural research centres supported by the Consultative Group on International Agricultural Research (CGIAR), the Food and Agriculture Organization of the United Nations (FAO) and partners from some 80 research and development institutes globally. Co-sponsors of the assessment, institutes that are interested in the results and help frame the assessment, are the Ramsar Convention, the Convention on Biological Diversity, the FAO and the CGIAR.

For production of this book, financial support from the governments of the Netherlands and Switzerland for the Comprehensive Assessment is appreciated.

David Molden
Series Editor
International Water Management Institute
Sri Lanka

Foreword

Most of the 852 million poor people in the world live in the developing countries of Asia and Africa, more so in drylands/rainfed areas. These rainfed areas are hotbeds of poverty, malnutrition, water scarcity, severe land degradation and poor physical and social infrastructure. Though rainfed agriculture constitutes 80% of global agriculture and plays a crucial role in achieving food security, increasing water scarcity and climate change threaten to affect rainfed areas and their peoples owing to their vulnerability to drought during the crop-growing season.

A Comprehensive Assessment (CA) of Water for Food and Water for Life, undertaken by a consortium of dedicated scientists from different institutions and rainfed areas and coordinated by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), revealed that global food security is possible with existing water resources. However, it calls for considerable efforts to improve water management to enhance water use efficiency in all sectors.

The Comprehensive Assessment demonstrated that current farmers' yields in rainfed areas are two- to fivefold lower than achievable potential yields and that current rainwater use efficiency is only 35–45% in most rainfed areas. Water used for food production in rainfed areas is almost threefold higher than that used in irrigated systems. Long-term experiments as well as yield gap analysis using crop simulation models and researchers' managed trials on farmers' fields have demonstrated that crop yields in rainfed areas can go up as high as 5 t/ha under semi-arid tropical Indian conditions. Large yield gaps exist in a number of rainfed crops such as maize, sorghum, pigeonpea, groundnut, soybean, pearl millet, chickpea, wheat and paddy in different countries of Asia and Africa.

Given such potential, the assessment concluded that yields could easily be doubled in rainfed areas of Asia and quadrupled in Africa, provided the adoption of available improved soil, water, crop and pest management options on farmers' fields is enhanced. It strongly favours abolishing the artificial divide between dryland and irrigated systems with its bias towards irrigation management.

Written by reputed specialists in rainfed agriculture, representing three premier international institutes – ICRISAT, the Stockholm Environment Institute (SEI) and the International Center for Agricultural Research in the Dry Areas (ICARDA), the book is a synthesis of the voluminous research undertaken by the CA team. It covers all aspects of rainfed agriculture, starting with its potential, current status, rainwater harvesting and supplementary irrigation to policies, approaches, institutions for upscaling, and impacts of integrated water management programmes in rainfed areas.

Rainfed Agriculture: Unlocking the Potential shows that the road to realizing a second Green Revolution lies in greening drylands to achieve global food security, reduce poverty and protect the environment. It is a very valuable resource material for researchers, policy makers, development investors, development workers and students.

William D. Dar
Director General
ICRISAT

Preface

The world is facing multiple challenges in the 21st century and those important challenges for humanity are poverty, food security, scarcity of water and, most importantly, new and complex challenges emerging due to global warming and climate change. Ever-increasing human population, changing lifestyle and dietary habits due to increased incomes, competing demand for the natural resources such as land and water, diversion of food crops for biofuel production and stagnating/lower growth rates for food production in the world are some of the main reasons for the food shortages and increasing food prices. The Comprehensive Assessment (CA) of Water for Food and Water for Life undertook a detailed and systematic assessment of the current status, future demands of food requirement and necessary water required to produce the same. The CA identified ten major questions at the beginning to be addressed holistically, covering different sectors of food production. A large number of institutions and scientists, policy makers and development workers worked together for 5 years and collected evidence and data, analysed critically and ran scenarios to address the most important issue of achieving food security with the looming water scarcity. These studies have culminated in a number of recommendations for each sector of food production. The CA has reached the conclusion that it is possible to meet the current as well as future food demands with the available water resources; however, it calls for new and innovative approaches (technical, institutional, policies, attitudes and habits) for food production and water management strategies, as the business as usual scenario will not meet the demand.

Rainfed agriculture plays, and will continue to play, an important role in global food production as 80% of agriculture is rainfed and contributes about 58% to the global food basket. In addition rainfed areas are also the hot-spots of poverty, malnutrition, water scarcity, severe land degradation, and poor physical and financial infrastructure. Under the CA, issues of rainfed agriculture were analysed in depth by a group of specialized institutions led by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, and the Stockholm Environment Institute (SEI), Sweden. The results of 2 years' comprehensive study by a large number of scientists working in rainfed agriculture are put together in this volume. The major finding of the CA of rainfed agriculture for food security is that the vast untapped potential of rainfed agriculture needs to be tapped as the current farmers' crop yields are lower by two- to fivefold than the potential, based on the clear documented evidence. The CA calls for upgrading of rainfed agriculture by adopting a new paradigm where artificial boundaries between rainfed and irrigated agriculture need to be discarded: science-based development by adopting a small catchment/watershed approach with integrated genetic and natural resource management (IGNRM), with community participation and more investments in rainfed areas. Innovative mechanisms to share the knowledge with the farmers and other stakeholders are very much needed as the traditional extension mechanisms worldwide, particularly in developing countries in Asia and Africa, are not effective. By upgrading rainfed agriculture in dryland areas in the semi-arid and humid tropics, efficiency of green water for food production can be substantially increased and pressure on blue water for food production can be reduced. Green water for food production is almost three times more than blue water (5000 km^3 versus 1800 km^3) globally.

This book, *Rainfed Agriculture: Unlocking the Potential*, opens up vistas of new, untapped opportunities to meet the challenges of enhancing food production with limited water resources. The small catchment/watershed management approach calls for new management tools and attitudes as communities play a critical role in conservation and enhancement of precious natural resources for sustainable development. Most importantly, the policy makers and development investors will find that these new opportunities are more productive not only in terms of economic parameters but also in terms of addressing issues of equity, gender, inclusive growth and, most importantly, for building resilience of the natural resources and communities to meet the future challenges including those due to globalization and climate change.

The book is organized into 14 chapters addressing the issues, starting with the past trends and future prospects, followed by zooming in on the global hotspots of rainfed agriculture, water resource implications of upgrading rainfed agriculture, tectonics–climate-linked natural soil degradation and its impact on rainfed agriculture, determinants of crop growth and yield in a changing climate, yield gap analysis, ‘can rainfed agriculture feed the world?’ scenario analysis, crop water productivity enhancement through genetic enhancement, water harvesting and supplemental irrigation in arid and SAT areas, integrated farm management practices, challenges of adoption and adaptation in smallholder agriculture and scaling-out community watershed management benefits in rainfed areas. This valuable resource book, with contributions from renowned scientists, will be useful for the spectrum of stakeholders including students, development investors, development agents, researchers and policy makers alike.

Suhas P. Wani,
Johan Rockström
and
Theib Oweis

Acknowledgements

Peter Hobbs, *Cornell University, USA*
Malin, Falkenmark, *Stockholm International Water Institute (SIWI), Sweden*
J.S. Samra, *National Rainfed Area Authority, India*
Jan Lundquist, *Stockholm International Water Institute (SIWI), Sweden*
A.V.R. Kesava Rao, *International Crops Research Institute for the Semi-Arid Tropics, India*
Steduto Pasquel, *Water Development and Management Unit (NRLW), Food and Agriculture Organization of the United Nations (FAO), Rome, Italy*
Jennie Barron, *Stockholm Environment Institute (SEI), UK*
A.K. Singh, *Indian Agricultural Research Institute (IARI), India*
R.B. Deshmukh, *Mahatma Phule Krishi Vidyapeeth, India*
P. Pathak, *International Crops Research Institute for the Semi-Arid Tropics, India*
Piara Singh, *International Crops Research Institute for the Semi-Arid Tropics, India*
Mohammed Osman, *Central Research Institute for Dryland Agriculture, India*
A.K. Misra, *National Research Centre for Women in Agriculture, India*
P.K. Joshi, *National Centre for Agricultural Economics and Policy Research, India*
K. Palanisami, *Centre for Agriculture & Rural Development Studies (CARDS), India*
V. Ratna Reddy, *Centre for Economics and Soil Studies (CESS), India*
K.V. Raju, *Institute For Social & Economic Change, India*
P.G. Chengappa, *University of Agricultural Sciences, India*
K.L. Sahrawat, *International Crops Research Institute for the Semi-Arid Tropics, India*

This page intentionally left blank

1 Rainfed Agriculture – Past Trends and Future Prospects

S.P. Wani,[1]* T.K. Sreedevi,[1] J. Rockström[2]*** and Y.S. Ramakrishna[3]******

[1] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Andhra Pradesh, India;* [2] *Stockholm Environment Institute (SEI), Stockholm, Sweden;* [3] *Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, Andhra Pradesh, India;*
*emails: *s.wani@cgiar.org; **t.sreedevi@cgiar.org; ***johan.rockstrom@sei.se; ****ramakrishna.ys@crida.ernet.in*

Introduction

The agricultural productivity has seen a rapid growth since the late 1950s due to new crop varieties, fertilizer use and expansion in irrigated agriculture. The world food production outstripped the population growth. However, there are regions of food insecurity. Of the 6.5 billion population today, about 850 million people face food insecurity. About 60% of them live in South Asia and sub-Saharan Africa. Food and crop demand is estimated to double in the next 50 years. According to a Comprehensive Assessment, it is possible to produce food – but it is probable that today's food production and environmental trends, if continued, will lead to crises in many parts of the world (Molden, 2007). The assessment has also indicated that the world's available land and water resources can satisfy future demands by taking the following steps:

- Investing to increase production in rainfed agriculture (rainfed scenario).
- Investing in irrigation (irrigation scenario).
- Conducting agricultural trade within and between countries (trade scenario).
- Reducing gross food demand by influencing diets, and reducing postharvest losses, including industrial and household waste.

Rainfed Agriculture

The importance of rainfed agriculture varies regionally but produces most food for poor communities in developing countries. In sub-Saharan Africa more than 95% of the farmed land is rainfed, while the corresponding figure for Latin America is almost 90%, for South Asia about 60%, for East Asia 65% and for the Near East and North Africa 75% (FAOSTAT, 2005). Most countries in the world depend primarily on rainfed agriculture for their grain food. Despite large strides made in improving productivity and environmental conditions in many developing countries, a great number of poor families in Africa and Asia still face poverty, hunger, food insecurity and malnutrition where rainfed agriculture is the main agricultural activity. These problems are exacerbated by adverse biophysical growing conditions and the poor socio-economic infrastructure in many areas in the semi-arid tropics (SAT). The SAT is the home to 38% of the developing countries' poor, 75% of whom live in rural areas. Over 45% of the world's hungry and more than 70% of its malnourished children live in the SAT.

Even with growing urbanization, globalization and better governance in Africa and Asia, hunger, poverty and vulnerability of livelihoods to natural

(eds S.P. Wani *et al.*)

and other disasters will continue to be greatest in the rural SAT. These challenges are complicated by climatic variability, the risk of climate change, population growth, health pandemics (AIDS, malaria), degrading natural resource base, poor infrastructure and changing patterns of demand and production (Ryan and Spencer, 2001). The majority of poor in developing countries live in rural areas; their livelihoods depend on agriculture and overexploitation of the natural resource base, pushing them into a downward spiral of poverty. The importance of rainfed sources of food weighs disproportionately on women, given that approximately 70% of the world's poor are women (WHO, 2000). Agriculture plays a key role for economic development (World Bank, 2005) and poverty reduction (Irz and Roe, 2000), with evidence indicating that every 1% increase in agricultural yields translates to a 0.6–1.2% decrease in the percentage of absolute poor (Thirtle *et al.*, 2002). On average for sub-Saharan Africa, agriculture accounts for 35% of gross domestic product (GDP) and employs 70% of the population (World Bank, 2000), while more than 95% of the agricultural area is rainfed (FAOSTAT, 2005), as elaborated in Box 1.1. Agriculture will continue to be the backbone of economies in Africa and South Asia in the foreseeable future. As most of the SAT poor are farmers and landless labourers, strategies for reducing poverty, hunger and malnutrition should be driven primarily by the needs of the rural poor, and should aim to build and diversify their livelihood sources. Substantial gains in land, water and labour productivity as well as better management of natural resources are essential to reverse the downward spiral of poverty and environmental degradation. Apart from the problems of equity, poverty and sustainability – and hence, the need for greater investment in SAT areas – studies have shown that research and development (R&D) investments in less-favoured semi-arid environments could provide high marginal payoffs in terms of generating new sources of economic growth. Renewed effort and innovative R&D strategies are needed to address these challenges, such as integrated natural resource management (INRM), which has been evolving within the 15 international agricultural research centres (IARC) of the Consultative Group for International Agricultural Research (CGIAR). The basic role of the 15 IARCs is to develop innovations for improving agricultural productivity and natural resource management (NRM) for addressing the problems of poverty, food insecurity and environmental degradation in developing countries. This effort has generated multiple and sizeable benefits (welfare, equity, environmental) (Kassam *et al.*, 2004). But much remains to be done in sub-Saharan Africa and less-favoured areas of South Asia.

Rainfed agriculture and water stress

There is a correlation between poverty, hunger and water stress (Falkenmark, 1986). The UN Millennium Development Project has identified the 'hot spot' countries in the world suffering from the largest prevalence of malnourishment. These countries coincide closely with those located in the semi-arid and dry subhumid hydroclimates in the world (Fig. 1.1), i.e. savannahs and steppe ecosystems, where rainfed agriculture is the dominating source of food and where water constitutes a key limiting factor to crop growth (SEI, 2005). Of the 850 million undernourished people in the world, essentially all live in poor, developing countries, which predominantly are located in tropical regions (UNSTAT, 2005).

Box 1.1. Agricultural growth: an underlying factor to economic growth (after van Koppen *et al.*, 2005).

Agriculture, the sector in which a large majority of the African poor make their living, is the engine of overall economic growth and, therefore, broad-based poverty reduction (Johnston and Mellor, 1961; World Bank, 1982; IFAD, 2001; DFID, 2002; Koning, 2002). This conclusion is based on analysis of the historical development paths of countries worldwide, and recent international reports have re-affirmed this position (e.g. Inter Academy Council, 2004; Commission for Africa, 2005; UN Millennium Project, 2005). Higher farm yields enhanced producer incomes, in cash and in kind, and created demand for agricultural labour. Thus, agricultural growth typically preceded economic growth in high-income countries and recent growth in the Asian Tigers such as Thailand, Malaysia, Indonesia, Vietnam and parts of China.

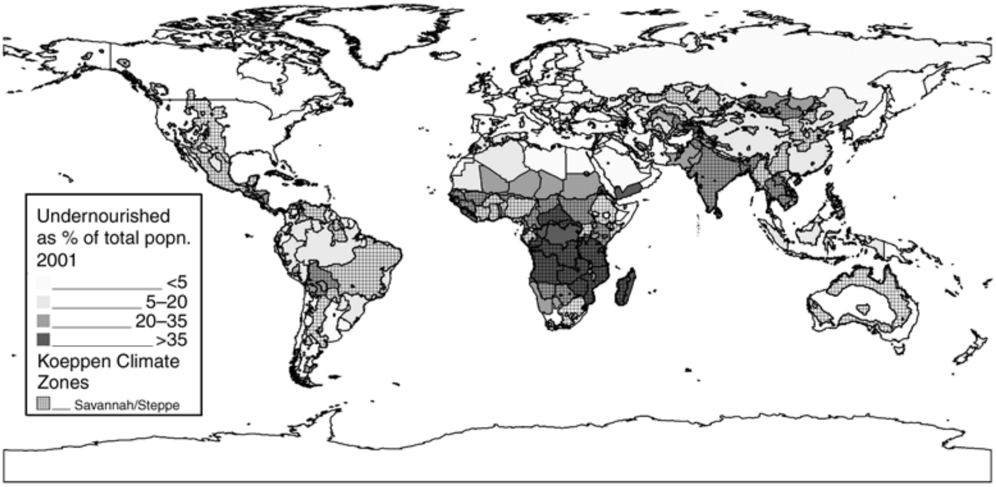


Fig. 1.1. The prevalence of undernourishment in developing countries (as percentage of population 2001–2002; UNSTAT, 2005), together with the distribution of semi-arid and dry subhumid hydroclimates in the world, i.e. savannah and steppe agroecosystems. These regions are dominated by sedentary farming subject to the world's highest rainfall variability and occurrence of dry spells and droughts.

Crop yields in rainfed areas

Since the late 1960s, agricultural land use has expanded by 20–25%, which has contributed to approximately 30% of the overall grain production growth during the period (FAO, 2002; Ramankutty *et al.*, 2002). The remaining yield outputs originated from intensification through yield increases per unit land area. However, the regional variation is large, as is the difference between irrigated and rainfed agriculture. In developing countries rainfed grain yields are on average 1.5 t/ha, compared with 3.1 t/ha for irrigated yields (Rosegrant *et al.*, 2002), and increase in production from rainfed agriculture has mainly originated from land expansion.

Trends are clearly different for different regions. With 99% rainfed production of main cereals such as maize, millet and sorghum, the cultivated cereal area in sub-Saharan Africa has doubled since 1960 while the yield per unit of land has been nearly stagnant for these staple crops (FAOSTAT, 2005). In South Asia, there has been a major shift away from more drought-tolerant, low-yielding crops such as sorghum and millet, while wheat and maize has approximately doubled in area since 1961 (FAOSTAT, 2005). During the same period, the yield per unit of land for maize and wheat has more than doubled (Fig. 1.2). For predominantly rainfed systems, maize crops per unit of land have nearly tripled and wheat more than doubled during the same time period.

Rainfed maize yield differs substantially between regions (Fig. 1.2a). In Latin America (including the Caribbean) it exceeds 3 t/ha, while in South Asia it is around 2 t/ha and in sub-Saharan Africa it only just exceeds 1 t/ha. This can be compared with maize yields in the USA or southern Europe, which normally amount to approximately 7–10 t/ha (most maize in these regions is irrigated). The average regional yield per unit of land for wheat in Latin America (including the Caribbean) and South Asia is similar to the average yield output of 2.5–2.7 t/ha in North America (Fig. 1.2b). In comparison, wheat yield in Western Europe is approximately twice as large (5 t/ha), while in sub-Saharan Africa it remains below 2 t/ha. In view of the historic regional difference in development of yields, there appears to exist a significant potential for raised yields in rainfed agriculture, particularly in sub-Saharan Africa and South Asia.

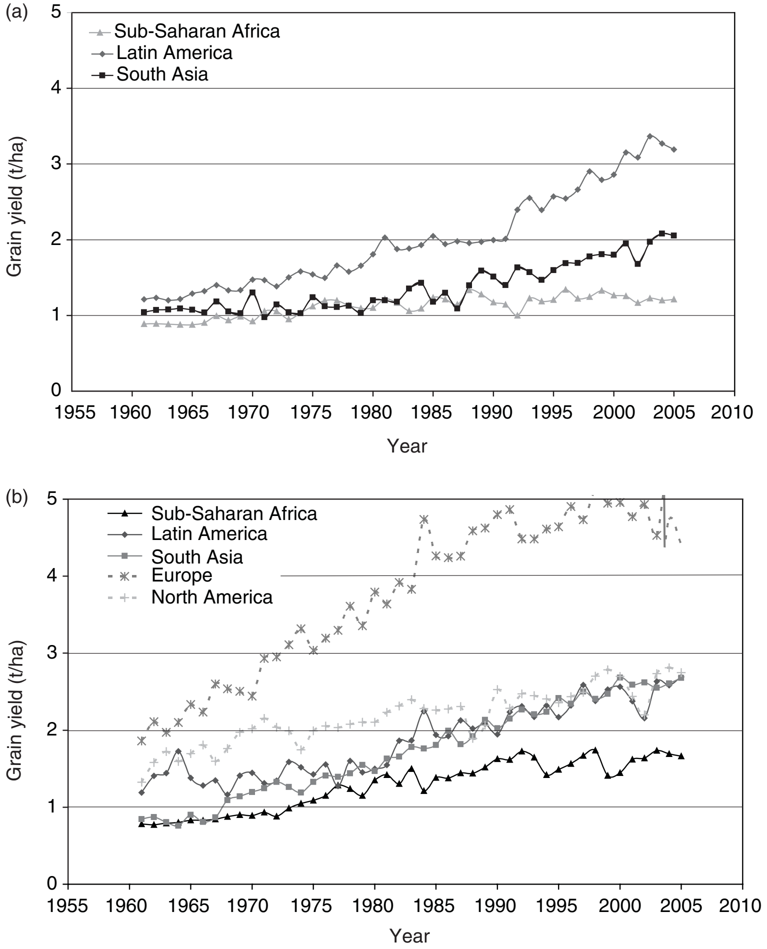


Fig. 1.2. Grain yield of predominantly rainfed maize (a) and wheat (b) for different regions during 1961–2000 (Source: FAOSTAT, 2005).

Rainfed Agriculture – a Large Untapped Potential

In several regions of the world rainfed agriculture generates among the world's highest yields. These are predominantly temperate regions, with relatively reliable rainfall and inherently productive soils. Even in tropical regions, particularly in the subhumid and humid zones, agricultural yields in commercial rainfed agriculture exceed 5–6 t/ha (Rockström and Falkenmark, 2000; Wani *et al.*, 2003a,b). At the same time, the dry subhumid and semi-arid regions have experienced the lowest yields and the weakest yield improvements per unit of land. Here, yields oscillate between 0.5 and 2 t/ha, with an average of 1 t/ha in sub-Saharan Africa, and 1–1.5 t/ha in South Asia, and central and west Asia and North Africa (CWANA) for rainfed agriculture (Rockström and Falkenmark, 2000; Wani *et al.*, 2003a,b).

Yield gap analyses carried out by Comprehensive Assessment for major rainfed crops in semi-arid regions in Asia and Africa and rainfed wheat in WANA reveal large yield gaps, with farmers' yields being a factor of two to four times lower than achievable yields for major rainfed crops. Detailed yield gap analysis for major rainfed crops in different parts of the world is discussed (see Chapter 6, this volume). Figure 1.3 illustrates examples of observed yield gaps in various countries in Africa, Asia and the Middle East. In countries in eastern and Southern Africa the yield gap is very large. Similarly, in many countries in west Asia, farmers' yields are less than 30% of achievable yields, while in some Asian countries the figure is closer to 50%. Historic trends present a growing yield gap between farmers' practices and farming systems that benefit from management advances (Wani *et al.*, 2003b).

Constraints in Rainfed Agriculture Areas

An insight into the inventories of natural resources in rainfed regions shows a grim picture of water scarcity, fragile environments, drought and land degradation due to soil erosion by wind and water, low rainwater use efficiency (35–45%), high population pressure, poverty, low investments in water use efficiency (WUE) measures, poor infrastructure and inappropriate policies (Wani *et al.*, 2003b,c; Rockström *et al.*, 2007). Drought and land degradation are interlinked in a cause and effect relationship, and the two combined are the main causes of poverty in farm households. This unholy nexus between drought, poverty and land degradation has to be broken to meet the Millennium Development Goal of halving the number of food-insecure poor by 2015. These rainfed areas are prone to severe land degradation. Reduction in the producing capacity of land due to wind and water erosion of soil, loss of soil humus, depletion of soil nutrients, secondary salinization, diminution and deterioration of vegetation cover as well as loss of biodiversity is referred to as land degradation. A global assessment of the extent and form of land degradation showed that 57% of the total area of drylands occurring in two major Asian countries, namely China (178.9 million ha) and India (108.6 million ha), are degraded (UNEP, 1997).

The root cause of land degradation is poor land use. Land degradation represents a diminished ability of ecosystems or landscapes to support the functions or services required for sustaining livelihoods. Over a period of time, continuing agricultural production, particularly in marginal and fragile lands, results in degradation of the natural resource base, with increasing impact on water resources. The following natural resources degradation and the relationship between major forms of soil degradation and water resources (Bossio *et al.*, 2007) require attention:

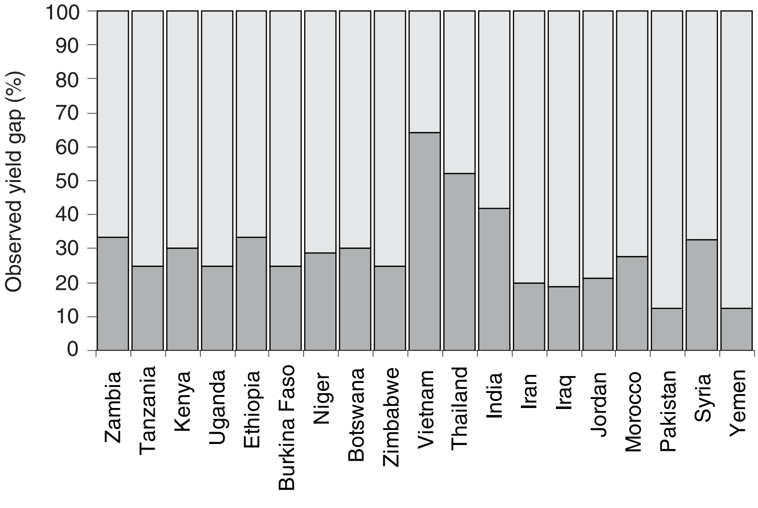


Fig. 1.3. Examples of observed yield gap (for major grains) between farmers' yields and achievable yields (100% denotes achievable yield level, and columns actual observed yield levels) (Source: derived from Rockström *et al.*, 2007).

- *Loss of organic matter and physical degradation of soil*: soil organic matter is integral to managing water cycles in ecosystems. Depleted levels of organic matter have significant negative impacts on infiltration and porosity, local and regional water cycles, water productivity, plant productivity, the resilience of agroecosystems and global carbon cycles.
- *Nutrient depletion and chemical degradation of soil*: pervasive nutrient depletion in agricultural soils is a primary cause of decreasing yields, low on-site water productivity and off-site water pollution. Salinity, sodicity and waterlogging threaten large areas of the world's most productive land and pollute groundwater.
- *Soil erosion and sedimentation*: accelerated on-farm soil erosion leads to substantial yield losses and contributes to downstream sedimentation and degradation of water bodies, a major cause of investment failure in water and irrigation infrastructure.
- *Water scarcity and pollution*: globally, agriculture is the main consumer of water, and water scarcity is a significant problem for farmers in Africa, Asia and the Near East. Agriculture is also the major contributor to non-point-source water pollution, while urbanization contributes increasingly large volumes of wastewater. Water quality problems can often be as severe as those of water availability but have yet to receive as much attention in developing countries.

Loss of organic matter and physical degradation of soil

Soil organic matter is integral to managing water cycle ecosystems. The impact of organic matter loss is not confined to production loss but also disturbs the water cycle. The decrease of soil organic matter, along with the associated faunal activities (aggravated by the use of pesticides and tillage practices), favours the collapse of soil aggregates and thus the crusting and the sealing of the soil surface. The result is reduced porosity, less infiltration and more run-off. Compaction of the soil surface by heavy machinery or overgrazing, for example, can cause overland flow, even on usually permeable soils. Such changes increase the risk of flooding and water erosion. Higher run-off concentrates in channels, causing rills and then gullies. Degradation thus changes the proportion of water flowing along pathways within catchments, with a tendency to promote rapid surface overland flow (run-off) and decrease subsurface flow. By controlling infiltration rates and water-holding capacity, soil organic matter plays a vital function in buffering yields through climatic extremes and uncertainty. Significantly, it is one of the most important biophysical elements that can be managed to improve resilience. Soil organic matter, furthermore, holds about 40% of the overall terrestrial carbon pool – twice the amount contained in the atmosphere. Poor agricultural practices are thus a significant source of carbon emissions and contribute to climate change.

Nutrient depletion and chemical degradation of soil

Globally, only half of the nutrients that crops take from the soil are replaced. This depletion of soil nutrients often leads to fertility levels that limit production and severely reduce water productivity. Shorter fallow periods do not compensate for losses in soil organic matter and nutrients, leading to the mining of soil nutrients. In many African, Asian and Latin American countries, the nutrient depletion of agricultural soils is so high that current agricultural land use is not sustainable. Nutrient depletion is now considered the chief biophysical factor limiting small-scale production in Africa (Drechsel *et al.*, 2004). Recent characterization of 4000 farmers' fields in different states across India revealed a widespread (80–100% fields) deficiency of zinc, boron and sulfur in addition to known deficiencies of macronutrients such as nitrogen and phosphorus (Sahrawat *et al.*, 2007). Such multi-nutrient deficiencies are largely due to diversion of organic manures to irrigated, high-value crops and more reliance on chemical fertilizers supplying macronutrients in pure form over a long period. Other important forms of chemical degradation are the depletion of trace metals such as zinc and iron, causing productivity declines and affecting human nutrition, acidification and salinization.

Soil erosion and sedimentation

Accelerated erosion, resulting in loss of nutrient-rich, fertile topsoil, occurs nearly everywhere where agriculture is practised and is irreversible. The torrential character of the seasonal rainfall creates high risk for the cultivated lands. In India, alone, some 150 million ha are affected by water erosion and 18 million ha by wind erosion. Soil loss ranged from 0.01 to 4.30 t/ha from sandy loam soils of Bundi district, Rajasthan, India, with the average annual rainfall of 760 mm as monitored during rainfall events over 4 years in a case study (Pathak *et al.*, 2006). Thus, erosion leaves behind an impoverished soil on the one hand and siltation of reservoirs and tanks on the other. The estimated nutrient losses in Thailand are indicated in Table 1.1 (Narongsak *et al.*, 2003). Soil erosion reduces crop yields by removing nutrients and organic matter. Erosion also interferes with soil–water relationships: the depth of soil is reduced, diminishing water storage capacity and damaging soil structure, thus reducing soil porosity. Downstream, the main impact of soil erosion is sedimentation, a major form of human-induced water pollution.

Water scarcity and pollution

Water scarcity is a significant problem for farmers in Africa, Asia and the Near East, where 80–90% of water withdrawals are used for agriculture (FAO/IIASA, 2000; Rosegrant *et al.*, 2002). Water, a finite resource, the very basis of life and the single most important feature of our planet, is the most threatened natural resource at the present time. Water is the most important driver for four of the Millennium Development Goals, as shown in Fig. 1.4. In the context of these four goals, the contribution of water resources management through direct interventions is suggested to achieve the milestones by 2015. However, in many SAT situations water quantity per se is not the limiting factor for increased productivity but its management and efficient use are the main yield determinants. Instead, the major water-related challenge for rainfed agriculture in semi-arid and dry subhumid regions is to deal with the extreme variability in rainfall, characterized by few rainfall events, high-intensity storms, and high frequency of dry spells and droughts. For example, in Kurnool district, one of the most drought-prone districts in Andhra Pradesh, India, there is a large variation in rainfall return years. The normal annual rainfall is about 660 mm, of which about 90% is received in the 6-month period of June to November. During a period of 55 years, normal rainfall (−19 to +19% in reference to normal rainfall) was received in 30 years, excess rainfall (>20% over normal rainfall) in 11 years and deficit rainfall (−20 to −59% of normal rainfall) in 14 years. It is therefore critical to understand the impact of hydro-climatic conditions and water management on yields in rainfed agriculture. Key constraints to rainwater productivity evidently differ greatly across the wide range of rainfall zones. In the arid regions, it is the absolute amount of water (so-called absolute water scarcity) that constitutes the major limiting factor in agriculture. In the semi-arid and dry subhumid tropical regions on the other hand, seasonal rainfall is generally adequate to significantly improve yields. Here, managing extreme rainfall variability in time and space is the largest water challenge. Only in the dry semi-arid and arid zones, considering mean rainfall, is absolute water stress common. In the wetter part of the semi-arid zone, and into the dry subhumid zone, rainfall generally exceeds crop water needs.

Table 1.1. Nutrient loss (t/year) in different regions of Thailand.

Region	Nitrogen	Phosphorus	Potassium
Northern	38,288	4,467	75,588
North-eastern	18,896	1,212	91,644
Eastern	17,890	1,074	30,860
Southern	17,310	453	13,254

Source: Land Development Department, Thailand.

Absolute water scarcity is thus rarely the major problem for rainfed agriculture. Still water scarcity is a key reason behind low agricultural productivity. To identify management options to upgrade rainfed agriculture it is therefore essential to assess different types of water stress in food production. Of particular importance is to distinguish between climate- and human-induced water stress, and the distinction between droughts and dry spells (Table 1.2). In semi-arid and dry subhumid

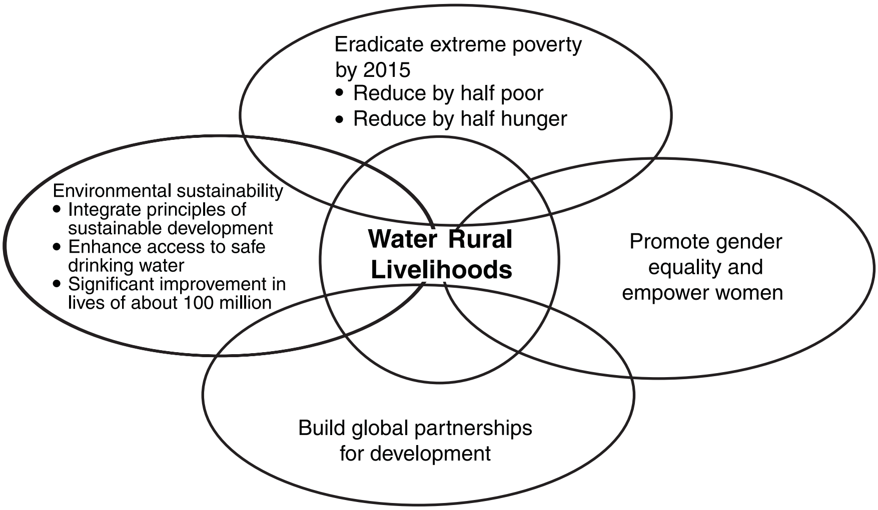


Fig. 1.4. Water is an important driver for achieving the Millennium Development Goals.

Table 1.2. Types of water stress and underlying causes in semi-arid and dry subhumid tropical environments[a].

Types of water stress	Dry spell	Drought
Meteorological	Occurrence: 2 out of 3 years Impact: yield reduction Cause: rainfall deficit of 2–5-week periods during crop growth	Occurrence: 1 out of 10 years Impact: complete crop failure Cause: seasonal rainfall below minimum seasonal plant water requirement
Agricultural (human induced)	Occurrence: >2 out of 3 years Impact: yield reduction or complete crop failure Cause: low plant water availability and poor plant water uptake capacity	Occurrence: >1 out of 10 years Impact: complete crop failure Cause: poor rainfall partitioning leads to seasonal soil moisture deficit to produce harvest

[a] Source: Falkenmark and Rockström (2004).

agroecosystems, rainfall variability generates dry spells (short periods of water stress during growth) almost every rainy season (Barron *et al.*, 2003), compared with meteorological droughts, which occur on average once every decade in moist semi-arid regions and up to twice every decade in dry semi-arid regions. When there is not enough rainfall to generate a crop, meteorological droughts result in complete crop failure. Such droughts cannot be bridged through agricultural water management, and instead social coping strategies are required, such as grain banks, relief food, local food storage and livestock sales. Dry spells, on the other hand, are manageable, i.e. investments in water management can bridge dry spells, which generally are 2–4 weeks of no rainfall during critical stages of plant growth (Box 1.2).

Even in regions with low variable rainfall, only a fraction actually forms soil moisture, i.e. green water resource, in farmers' fields. In general, only 70–80% of the rainfall is available to the plants as soil moisture, and on poorly managed land the fraction of plant-available water can be as low as 40–50% (Falkenmark and Rockström, 2004). This leads to agricultural dry spells and droughts, which are not

Box 1.2. Dry spell occurrence and yield implications in savannah agroecosystems.

Barron *et al.* (2003) studied dry spell occurrence in semi-arid locations in Kenya and Tanzania and found that meteorological dry spells of >10 days occurred in 70% of seasons during the flowering stage of the crop (maize), which is very sensitive to water stress. Regions with similar seasonal rainfall can experience different dry spell occurrence. In the semi-arid Nandavaram watershed, Andhra Pradesh, India, with approximately 650 mm of rainfall, there is a high risk of dry spell occurrence (>40% risk) during the vegetative and flowering stages of the crop, compared with semi-arid Xiaoxingcun, Southern China, receiving similar rainfall but with only a 20% risk of early season dry spells (Kesava Rao *et al.*, 2007).

caused primarily by rainfall deficiencies but instead are due to management-related problems with the on-farm water balance. The occurrence of agricultural droughts and dry spells are thus not only an indicator of poor agricultural water management but also a sign of a large opportunity to improve yields, as these droughts and dry spells are to a large degree manageable.

In addition, imbalanced use of nutrients in agriculture by the farmers results in mining of soil nutrients. Recent studies in India revealed that 80–100% of the farmers' fields were found to be critically deficient in zinc, boron and sulfur in addition to nitrogen and organic carbon (Rego *et al.*, 2005; Wani *et al.*, 2006a). Overall the constraints of rainfed production are many (Box 1.3). If the current production practices are continued, developing countries in Asia and Africa will face a serious food shortage in the very near future. The major constraints for low on-farm yields and large yield gap are:

- Inappropriate NRM practices followed by the farmers.
- Lack of knowledge.
- Low investments in rainfed agriculture.
- Lack of policy support and infrastructure including markets and credit.
- Traditional cultivars.
- Low use of fertilizers.
- Low rainwater use efficiency.
- Pests and diseases.
- Compartmental approach.

Potential of Rainfed Agriculture

In several regions of the world rainfed agriculture generates the world's highest yields. These are predominantly temperate regions, with relatively reliable rainfall and inherently productive soils. Even in tropical regions, particularly in the subhumid and humid zones, agricultural yields in commercial rainfed agriculture exceed 5–6 t/ha (Rockström and Falkenmark, 2000; Wani *et al.*, 2003a,b; Rockström *et al.*, 2007). Evidence from a long-term experiment at the International Crops Research Institute for the Semi-Arid

Box 1.3. Constraints identified by the stakeholders in Shekta watershed, Maharashtra, India.

- Land degradation because of felling trees, shrubs and free grazing had intensified and added to the problems of excessive run-off and soil erosion.
- Due to irregular and insufficient rainfall, there was severe scarcity of drinking water throughout the year.
- During summer, wells dried up frequently and the water table declined, leading to high intensity of water requirement in a short period and thus influencing crop failures, drought, etc.
- Livestock production in the village is limited mainly to goats, sheep, indigenous cows, buffaloes and bullocks but there is not much emphasis on breed improvement, animal nutrition and health for improving productivity.
- The socio-economic status of the people is very low and the education of children, especially female, is low although the village has set up a primary school (up to 9 years of age) in the village itself.
- The problem of market access and price fluctuations compounds the problems of inappropriate prices for the farm produce and decision making.
- At initial stages of watershed development the decision of the community to ban free grazing disturbed the livelihood of small farmers, shepherds and families owning small ruminants.

Tropics (ICRISAT), Patancheru, India, since 1976 demonstrated the virtuous cycle of persistent yield increase through improved land, water and nutrient management in rainfed agriculture. Improved systems of sorghum/pigeonpea intercrops produced higher mean grain yields (5.1 t/ha) compared with 1.1 t/ha, the average yield of sole sorghum in the traditional (farmers') post-rainy system, where crops are grown on stored soil moisture (Fig. 1.5). The annual gain in grain yield in the improved system was 82 kg/ha/year compared with 23 kg/ha/year in the traditional system. The large yield gap between attainable yield and farmers' practice as well as between the attainable yield of 5.1 t/ha and potential yield of 7 t/ha shows that a large potential of rainfed agriculture remains to be tapped. Moreover, the improved management system is still continuing to provide an increase in productivity as well as improving soil quality (physical, chemical and biological parameters) along with increased carbon sequestration of 330 kg C/ha/year (Wani *et al.*, 2003a). Yield gap analyses, undertaken for the Comprehensive Assessment of Water for Food and Water for Life, for major rainfed crops in semi-arid regions in Asia (Fig. 1.6) and Africa and rainfed wheat in WANA reveal large yield gaps, with farmers' yields being a factor of two to four lower than achievable yields for major rainfed crops grown in Asia and Africa (Rockström *et al.*, 2007). At the same time, the dry subhumid and semi-arid regions experience the lowest yields and the lowest productivity improvements. Here, yields oscillate between 0.5 and 2 t/ha, with an average of 1 t/ha, in sub-Saharan Africa, and 1–1.5 t/ha in SAT Asia, Central Asia and WANA (Rockström and Falkenmark 2000; Wani *et al.*, 2003a,b; Rockström *et al.*, 2007).

Farmers' yields continue to be very low compared with the experimental yields (attainable yields) as well as simulated crop yields (potential yields), resulting in a very significant yield gap between actual and attainable rainfed yields. The difference is largely explained by inappropriate soil, water and crop management options used at the farm level, combined with persistent land degradation.

The vast potential of rainfed agriculture needs to be unlocked through knowledge-based management of natural resources for increasing productivity and income to achieve food security in the developing world. Soil and water management play a very critical role in increasing agricultural productivity in rainfed areas in the fragile SAT systems.

New Paradigm in Rainfed Agriculture

Current rainfed agriculture cannot sustain the economic growth and food security needed.

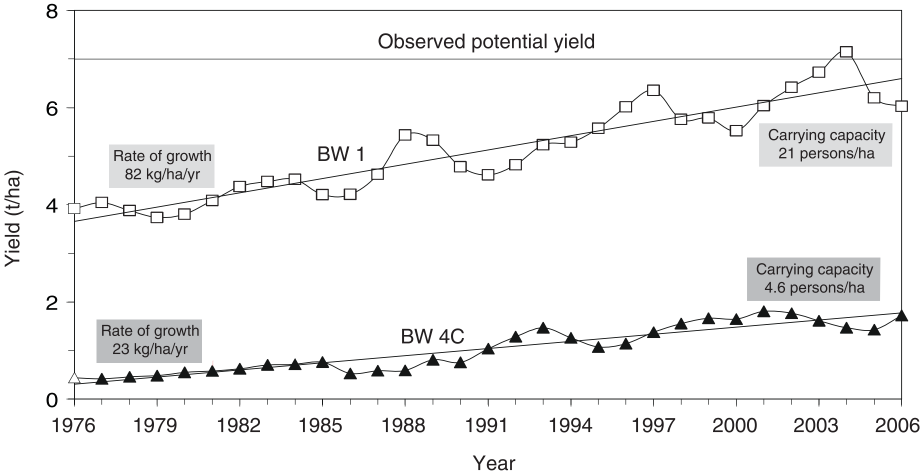


Fig. 1.5. Three-year moving average of sorghum and pigeonpea grain yield under improved and traditional management in a deep vertisol catchment at Patancheru, India.

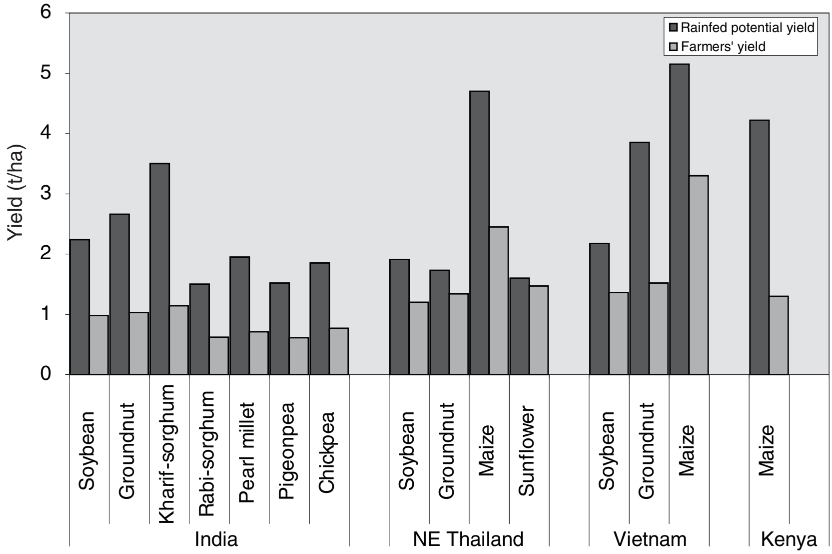


Fig. 1.6. Yield gap of important rainfed crops in different countries (Source: Rockström *et al.*, 2007).

There is an urgent need to develop a new paradigm for soil and water management. We need to have a holistic approach based on converging all the necessary aspects of natural resource conservation, their efficient use, production functions and income-enhancement avenues through value-chain and enabling policies and much-needed investments in rainfed areas.

Integrated genetic and natural resource management

Traditionally, crop improvement and NRM were seen as distinct but complementary disciplines. ICRISAT is deliberately blurring these boundaries to create the new paradigm of IGNRM (integrated genetic and natural resource management) (Twomlow *et al.*, 2006). Improved varieties and improved resource management are two sides of the same coin. Most farming problems require integrated solutions, with genetic, management-related and socio-economic components. In essence, plant breeders and NRM scientists must integrate their work with that of private- and public-sector change agents to develop flexible cropping systems, which can respond to rapid changes in market opportunities and climatic conditions. It is time to stop debate on genetic enhancement or NRM and adopt the IGNRM approach converging genetic, NRM, social and institutional aspects with market linkages. The systems approach looks at various components of the rural economy – traditional food grains, new potential cash crops, livestock and fodder production, as well as socio-economic factors such as alternative sources of employment and income. Crucially the IGNRM approach is participatory, with farmers closely involved in technology development, testing and dissemination.

Technologies must match not only the crop or livestock enterprise and the biophysical environment but also the market and investment environment, including seed availability. Plant breeders and NRM scientists must integrate their work with change agents (both public and private sector), and work with target groups to develop flexible cropping systems that can respond to changes in market opportunities. Rather than pursuing a single correct answer, we need to look for multiple solutions tailored to the requirements of contrasting environments and diverse sets of households. These include small and marginal farmers, female-headed households, HIV/AIDS-affected households, those lacking draft power, farmers with poor market access as well as households with good market access and better commercial production opportunities. In the rainfed areas, to improve livelihoods the approach has to be a business one through marketable surplus production through diversified farming systems with necessary market linkages and institutional arrangements.

ICRISAT's studies in Africa and Asia have identified several key constraints to more widespread technology adoption (Ryan and Spencer, 2001). Other institutes have independently reached similar conclusions for other agroecosystems. So there is general agreement on the key challenges before us. These are:

- Lack of a market-oriented smallholder production system where research is market-led, demand-driven and follows the commodity chain approach to address limiting constraints along the value chain. For example, ICRISAT's work on community watersheds for improving livelihoods in Asia and developing groundnut markets in Malawi aims to address this issue.
- Poor research–extension–farmer linkages, which limit transfer and adoption of technology. For example, ICRISAT's work on Farmer Field Schools in Africa and the consortium approach to integrated management of community watersheds in Asia aims to strengthen these linkages.
- Need for policies and strategies on soil, water and biodiversity to offset the high rate of natural resource degradation. These issues are central to ICRISAT's consortium approach to integrated community watershed management.
- Need to focus research on soil fertility improvement, soil and water management, development of irrigation, promotion of integrated livestock–wildlife–crop systems and development of drought-mitigation strategies. These issues are addressed by several ICRISAT programmes, e.g. low-input soil fertility approaches in Africa; micronutrient research in Asia, and the Sahelian Eco-Farm.
- Need to strengthen capacities of institutions and farmers' organizations to support input and output marketing and agricultural production systems. Such capacity building is a primary goal of the Soil Water Management Network (SWMnet) of ASARECA (Association for Strengthening Agricultural Research in Eastern and Central Africa) and the Eastern and Central Africa Regional Sorghum and Millet Network (ECARSAM) in eastern and central Africa, and of seed systems/germplasm improvement networks globally.
- Poor information flow and lack of communication on rural development issues. These are being addressed by ICRISAT's VASAT Consortium (Virtual Academy for the Semi-Arid Tropics) globally and specifically ICRISAT's Bio-economic Decision Support work with partners in West Africa.
- Need to integrate a gender perspective in agricultural research and training as seen in ICRISAT's work on HIV/AIDS amelioration in India and Southern Africa.

Crop improvement plays an important role in addressing each of these issues, and thus ICRISAT has expanded the INRM paradigm to specifically emphasize the role crops and genetic improvement can play in enabling SAT agriculture to achieve its potential. Thus, the institute is seeking to embrace an overall philosophy of IGNRM. There is clear evidence from Asia and Africa (Fig. 1.7) that the largest productivity gains in the SAT can come from combining new varieties with improved crop management and NRM (Table 1.3).

A major research challenge faced in INRM is to combine the various 'information bits' derived from different stakeholders, and distil these into decision rules that they can use (Snapp and Heong, 2003). ICRISAT's participatory research in Southern Africa demonstrated that with micro-dosing alone or in combination with available animal manures farmers could increase their yields by 30–100% by applying as little as 10 kg of nitrogen per hectare (Dimes *et al.*, 2005; Ncube *et al.*, 2006; Rusike *et al.*, 2006) (Fig. 1.8).

In much of agricultural research, the multidisciplinary team approach has often run into difficulties in achieving impact because of the perceived disciplinary hierarchy. The IGNRM approach in the Community Watershed Consortium pursues integration of the knowledge and products of the various research disciplines into useful extensions messages for development workers that can sustain increased yields for a range of climatic and edaphic conditions. A similar attempt at integration

Table 1.3. Yield advantages observed with different crop cultivars and improved management in Sujala watersheds of Karnataka, India during 2005–2006 seasons.

	Yield improvement (%)		
Crop	Local Cultivar+IMP[a]	HYV+FP[b]	HYV[c]+IMP
Finger millet	74	22–52	103–123
Groundnut	27	13–36	47–83
Soybean	62	0	83
Sunflower	67	54–150	152–230
Maize	–	26	70
Sorghum	–	–	31

[a] IMP = improved management practice; [b] FP = farmers' practice; [c] HYV = high-yielding variety.

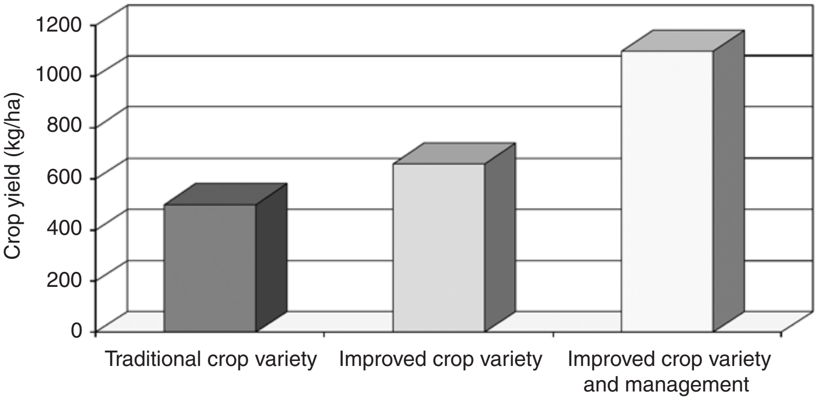


Fig. 1.7. Contribution of different technology components on sorghum yield, as observed in on-farm trials in Zimbabwe (Source: Heinrich and Rusike, 2003).

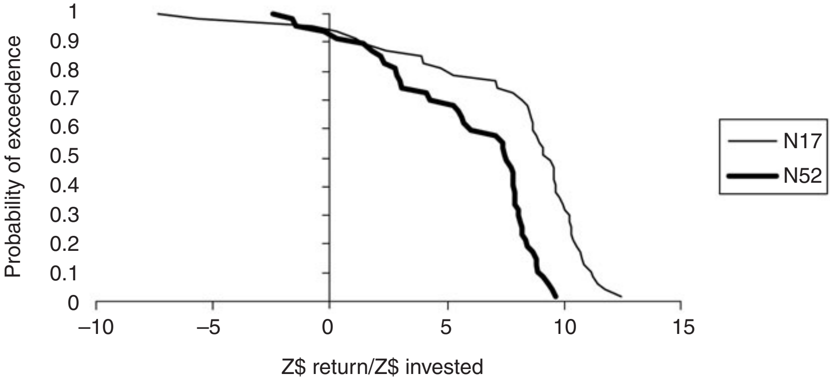


Fig. 1.8. The probability of exceeding given rates of return on nitrogen (N)-fertilizer investment on maize production at 17 and 52 kg N/ha at Masvingo, Zimbabwe (Source: Dimes, 2005).

was made for pearl millet production in Mali for a range of possible climatic scenarios (Table 1.4).

In Asia, the integrated community watershed management approach that aims to promote income-generating and sustainable crop and livestock production options as an important component of improved management of watershed landscapes is a live example of how IGNRM led to significant benefits in a poor area (Tables 1.5 and 1.6, and Fig. 1.9) and this holistic participatory approach is transforming the lives of resource-poor small and marginal farmers in the dryland areas of Asia (Wani *et al.*, 2006a).

ICRISAT and the national agricultural research systems (NARS) in Asia have developed in partnership an innovative and upscalable consortium model for managing watersheds holistically. In this approach, rainwater management is used as an entry point activity starting with *in-situ* conservation of rainwater and converging the benefits of stored rainwater into increased productivity by using improved crops, cultivars, suitable nutrient and pest management practices, and land and water management practices (Table 1.6). The IGNRM approach has enabled communities not only to harness the benefits of watershed management but also to achieve much of the potential from improved varieties from a wider range of crops. The households' incomes and overall productivity have more than doubled throughout selected benchmark sites in Asia (Fig. 1.9 and Table 1.7). The benefits accrue not only to landholding households but also to the landless marginalized

Table 1.4. Effect of climate variability on pearl millet crop performance and integrated genetic natural resource management (IGNRM) options in Mali (adapted from ICRISAT, 2006).

Climate parameters	Effects on crops and natural resources	IGNRM options
Late onset of rains	Shorter rainy season, risk that long-cycle crops will run out of growing time	Early-maturing varieties, exploitation of photoperiodism, P fertilizer at planting
Early drought	Difficult crop establishment and need for partial or total re-sowing	P fertilizer at planting, water harvesting and run-off control, delay sowing (but poor growth due to N flush), exploit seedling heat and drought tolerance
Mid-season drought	Poor seed setting and panicle development, fewer productive tillers, reduced grain yield per panicle/plant	Use of pearl millet variability: differing cycles, high-tillering cultivars, optimal root traits, etc.; water harvesting and run-off control
Terminal drought	Poor grain filling, fewer productive tillers	Early-maturing varieties, optimal root traits, fertilizer at planting, water harvesting and run-off control
Excessive rainfall	Downy mildew and other pests, nutrient leaching	Resistant varieties, pesticides, N fertilizer at tillering
Increased temperature	Poor crop establishment (desiccation of seedlings), increased transpiration, faster growth	Heat-tolerance traits, crop residue management, P fertilizer at planting (to increase plant vigour), large number of seedlings per planting hill
Unpredictability of drought stress	See above	Phenotypic variability, genetically diverse cultivars
Increased CO_2 levels	Faster plant growth through increased photosynthesis, higher transpiration	Promote positive effect of higher levels through better soil fertility management
Increased occurrence of dust storms at onset of rains	Seedlings buried and damaged by sand particles	Increase number of seedlings per planting hill, mulching, ridging (primary tillage)
Increased dust in the atmosphere	Lower radiation, reduced photosynthesis	Increase nutrient inputs (i.e. K)

Table 1.5. Effect of integrated water management interventions on run-off and soil erosion in Adarsha watershed, Andhra Pradesh, India.

		Run-off (mm)		Peak run-off rate (m^3/s/ha)		Soil loss (t/ha)	
Year	Rainfall (mm)	Untreated	Treated	Untreated	Treated	Untreated	Treated
1999	584	16	NI[a]	0.013	NI[a]	NI[a]	NI[a]
2000	1161	118	65	0.235	0.230	4.17	1.46
2001	612	31	22	0.022	0.027	1.48	0.51
2002	464	13	Nil	0.011	Nil	0.18	Nil
2003	689	76	44	0.057	0.018	3.20	1.10
2004	667	126	39	0.072	0.014	3.53	0.53
2005	899	107	66	0.016	0.014	2.82	1.20
2006	715	110	75	0.003	0.001	2.47	1.56
Mean	724	75 (10.4%)	44 (6.1%)	0.054	0.051	2.55	1.06

[a] Not installed.

Source: Sreedevi *et al.* (2007).

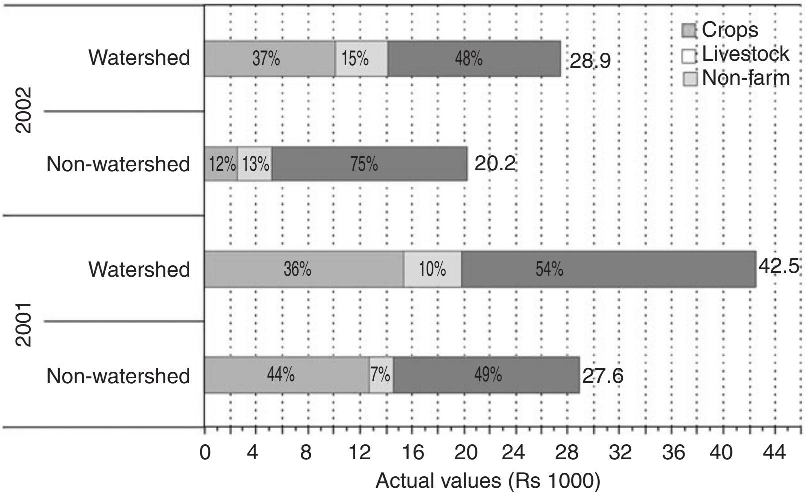


Fig. 1.9. Effect of integrated watershed management on flow of household net income (Source: ICRISAT Data – Adarsha watershed, Andhra Pradesh, India).

groups through the creation of greater employment opportunities. The greater resilience of crop income in the watershed villages during the drought year in 2002 is particularly noteworthy (Fig. 1.9). While the share of crops in household income declined from 44% to 12% in the non-project villages, crop income remained largely unchanged from 36% to 37% in the watershed village. The loss in household income in the non-project villages was largely compensated by migration and non-farm income which increased from 49% in an average year to 75% during the drought year in 2002. Much of this gain originates from improved soil fertility management and increased availability of irrigation water and integration of improved cultivars and cropping patterns into the watershed systems.

While the INRM approach has made significant contributions in re-orienting research for sustainable management of natural resources, there is now a need to create clear synergies with germplasm improvement and the income and

Table 1.6. Crop yields in Adarsha watershed, Kothapally, during 1999–2007.

		Yield (kg/ha)									
Crop	1998 base-line yield	1999–2000	2000–2001	2001–2002	2002–2003	2003–2004	2004–2005	2005–2006	2006–2007	Average yields	SE±
Sole maize	1500	3250	3750	3300	3480	3920	3420	3920	3635	3640	283.3
Improved intercropped maize	–	2700	2790	2800	3083	3129	2950	3360	3180	3030	263.0
Traditional intercropped maize	–	700	1600	1600	1800	1950	2025	2275	2150	1785	115.6
Improved intercropped pigeonpea		640	940	800	720	950	680	925	970	860	120.3
Traditional intercropped pigeonpea	190	200	180	–	–	–	–	–	–	190	–
Improved sole sorghum	–	3050	3170	2600	2425	2290	2325	2250	2085	2530	164.0
Traditional sole sorghum	1070	1070	1010	940	910	952	1025	1083	995	1000	120.7
Intercropped sorghum	–	1770	1940	2200	–	2110	1980	1960	1850	1970	206.0

Table 1.7. The effect of integrated watershed interventions on alternative sources of household income (Rs 1000).

Year	Village group[a]	Statistics	Crop income	Livestock income	Off-farm income	Household income
2001 (average year)	Non-project	Mean income	12.7	1.9	14.3	28.9
		Share of total income (%)	44.0	6.6	49.5	100.0
	Watershed project	Mean income	15.4	4.4	22.7	42.5
		Share of total income (%)	36.2	10.4	53.4	100.0
2002 (drought year)	Non-project	Mean income	2.5	2.7	15.0	20.2
		Share of total income (%)	12.2	13.3	74.5	100.0
	Watershed project	Mean income	10.1	4.0	13.4	27.6
		Share of total income (%)	36.7	14.6	48.7	100.0

[a] The sample size is n = 60 smallholder farmers in each group (ICRISAT data).

livelihood strategies of resource users. Thus the IGNRM approach espoused by ICRISAT now encompasses seed technologies and germplasm improvement as one of the important pillars for sustainable intensification and productivity improvement of agriculture in the SAT. Recent experiences at ICRISAT with projects that pursue the IGNRM approach (e.g. integrated management of community watersheds) provide optimism about the effectiveness and suitability of this approach.

Soil health: an important driver for enhancing water use efficiency

Soil health is severely affected due to land degradation and is in need of urgent attention. ICRISAT's on-farm diagnostic work in different community watersheds in different states of India as well as in China, Vietnam and Thailand showed severe mining of soils for essential plant nutrients. Exhaustive analysis showed that 80–100% of farmers' fields are deficient not only in total nitrogen but also in micronutrients such as zinc and boron and secondary nutrients such as sulfur (Table 1.8). In addition, soil organic matter, an important driving force for supporting biological activity in soil, is very much in short supply, particularly in tropical countries. Management practices that augment soil organic matter and maintain it at a threshold level are needed. Farm bunds could be productively used for growing nitrogen-fixing shrubs and trees to generate nitrogen-rich loppings. For example, growing *Gliricidia sepium* at a close spacing of 75 cm on farm bunds could provide 28–30 kg nitrogen per ha annually in addition to valuable organic matter. Also, large quantities of farm residues and other organic wastes could be converted into a valuable source of plant nutrients and organic matter through vermicomposting (Wani *et al.*, 2005). Strategic long-term catchment research at ICRISAT has shown that legume-based systems, particularly with pigeonpea, could sequester 330 kg carbon up to 150 cm depth in vertisols at Patancheru, India under rainfed conditions (Wani *et al.*, 2003a). Under the National Agricultural Technology Project (NATP), ICRISAT, the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), the Central Research Institute for Dryland Agriculture (CRIDA) and the Indian Institute of Soil Science (IISS) have identified carbon sequestering systems for alfisols and vertisols in India (ICRISAT, 2005). Integrated nutrient management strategies go a long way in improving soil health for enhancing WUE and increasing farmers' incomes.

Table 1.8. Percentage of farmers' fields deficient in soil nutrients in different states of India.

State	No. of farmers' fields	OC[a] (%)	AvP[a] (ppm)	K (ppm)	S (ppm)	B (ppm)	Zn (ppm)
Andhra Pradesh	1927	84	39	12	87	88	81
Karnataka	1260	58	49	18	85	76	72
Madhya Pradesh	73	9	86	1	96	65	93
Rajasthan	179	22	40	9	64	43	24
Gujarat	82	12	60	10	46	100	82
Tamil Nadu	119	57	51	24	71	89	61
Kerala	28	11	21	7	96	100	18

[a] OC = organic carbon; AvP = available phosphorus.

Often, soil fertility is the limiting factor to increased yields in rainfed agriculture (Stoorvogel and Smaling, 1990). Soil degradation, through nutrient depletion and loss of organic matter, causes serious yield decline closely related to water determinants, as it affects water availability for crops, due to poor rainfall infiltration, and plant water uptake, due to weak roots. Nutrient mining is a serious problem in smallholder rainfed agriculture. In sub-Saharan Africa soil nutrient mining is particularly severe. It is estimated that approximately 85% of African farmland in 2002–2004 experienced a loss of more than 30 kg/ha of nutrients per year (IFDC, 2006).

In India, farmers' participatory watershed management trials in more than 300 villages demonstrated that the current subsistence farming has depleted soils not only in macronutrients but also in micronutrients such as zinc and boron and secondary nutrients such as sulfur beyond the critical limits. A substantial increase in crop yields was experienced after micronutrient amendments, and a further increase by 70–120% when both micronutrients and adequate nitrogen and phosphorus were applied, for a number of rainfed crops (maize, sorghum, mung bean, pigeonpea, chickpea, castor and groundnut) in farmers' fields (Rego *et al.*, 2005).

Therefore, investments in soil fertility directly improve water management. Rainwater productivity (i.e. total amount of grain yield per unit of rainfall) was significantly increased in the example above as a result of micronutrient amendment. The rainwater productivity for grain production was increased by 70–100% for maize, groundnut, mung bean, castor and sorghum by adding boron, zinc and sulfur (Rego *et al.*, 2005). In terms of net economic returns, rainwater productivity was substantially higher by 1.50 to 1.75 times (Rego *et al.*, 2005). Similarly, rainwater productivity increased significantly when adopting integrated land and water management options as well as use of improved cultivars in semi-arid regions of India (Wani *et al.*, 2003b).

Water resources management

For enhancing rainwater use efficiency in rainfed agriculture, the management of water alone cannot result in enhanced water productivity as the crop yields in these areas are limited by additional factors than water limitation. ICRISAT's experience in rainfed areas has clearly demonstrated that, more than water quantity per se, management of water resources is the limitation in the SAT regions (Wani *et al.*, 2006a).

As indicated by Agarwal (2000), India would not have to suffer from droughts if local water balances were managed better. Even during drought years, watershed development efforts of improving rainfall management have benefited Indian farmers. For example, villages benefiting from watershed management projects increased food produce and market value by 63% compared with the non-project village even during drought years (Wani *et al.*, 2006b). An analysis in Malawi indicates that since the late 1970s only a fraction of the years that have been politically proclaimed as drought years actually were years subject to meteorological droughts (i.e. years where rainfall totals fall under minimum water needs to produce food at all) (Mwale, 2003). This is supported by Glantz (1994), who pointed out that agricultural droughts, where drought in the root zone is caused primarily by a poorly performing water balance, are more common than meteorological droughts. Furthermore, political droughts, where failures in the agricultural sector are blamed on drought, are commonplace.

Given the previous message the question arises, why is everybody blaming drought when there are famines and food shortages? The answer is that even if there is no drought in terms of rainfall, the crop may suffer from drought in the root zone, in terms of lack of green water or soil moisture. Often land degradation and poor management of soil fertility and crops are the major and more frequent causes of 'droughts'. These are referred to as agricultural droughts – where rainfall partitioning in the farmers' fields causes water stress. Available water as rainfall is not utilized fully for plant growth. The main cause is therefore management rather than meteorologically significant rainfall deficits.

Evidence from water balance analyses on farmers' fields around the world shows that only a small fraction, generally less than 30% of rainfall, is used as productive green water flow (plant transpiration) supporting plant growth (Rockström, 2003). Moreover, evidence from sub-Saharan Africa shows that this range varies from 15 to 30% of rainfall, even in the regions generally perceived as 'water scarce' (Fig. 1.10). This range is even lower on severely degraded land or land where yields are lower than 1 t/ha. Here, as little as 5% of rainfall may be used productively to produce food. In arid areas typically as little as 10% of the rainfall is consumed as productive green water flow (transpiration) with 90% flowing as non-productive evaporation flow, i.e. no or very limited blue water generation (Oweis and Hachum, 2001). For temperate arid regions, such as WANA, a larger portion of the rainfall is generally consumed in the farmers' fields as productive green water flow (45–55%) as a result of higher yield levels (3–4 t/ha as compared with 1–2 t/ha). Still, 25–35% of the rainfall flows as non-productive green water flow, with only some 15–20% generating blue water flow.

This indicates a large window of opportunity. Low current agricultural yields in rainfed agriculture, which are often blamed on rainfall deficits, are in fact often caused by other factors than rainfall. Still, what is possible to produce on-farm will not always be produced, especially not by resource-poor, small-scale farmers. The farmers' reality is influenced by other constraints such as labour shortage, insecure land ownership, capital constraints and limitation in human capacities. All these factors influence how farming is done, in terms of timing of operations, effectiveness of farm operations (e.g. weeding and pest management), investments in fertilizers and pesticides, use of improved crop varieties, water management, etc. The final produce in the farmers' field is thus strongly affected by social, economic and institutional conditions.

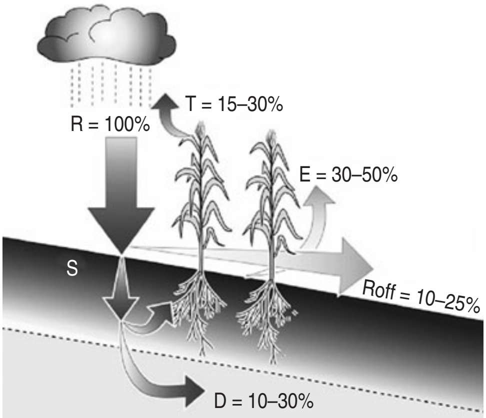


Fig. 1.10. General overview of rainfall partitioning in farming systems in the semi-arid tropics of sub-Saharan Africa, indicating the large portion of rainfall (R) which even in semi-arid farming systems is lost from the farm scale through drainage (D), surface run-off (Roff) and non-productive evaporation (E). The remainder is transpiration (T) (Source: Rockström *et al.*, 2007).

High risk and increase with climate change

Rainfed agriculture is a risky business due to high spatial and temporal variability of rainfall. Rainfall is concentrated in short rainy seasons (approximately 3–5 months), with few intensive rainfall events, which are unreliable in temporal distribution, manifested by high deviations from the mean rainfall (coefficients of variation of rainfall as high as 40% in semi-arid regions) (Wani *et al.*, 2004). In fact, even if water is not always the key limiting factor for yield increase, rainfall is the only truly random production factor in the agricultural system. This is manifested through high rainfall variability causing recurrent flooding, droughts and dry spells.

Established but incomplete evidence suggests that the high risk for water-related yield loss makes farmers avert risk, which in turn determines farmers' perceptions on investments in other production factors (such as labour, improved seed and fertilizers). Smallholder farmers are usually aware of the effects of shortage and/or variability of soil moisture on the variety, quantity and quality of produce, leading to a very narrow range of options for commercialization. This, together with the fluctuations in yields, makes it hard for resource-poor men and women in semi-arid areas to respond effectively to opportunities made possible by emerging markets, trade and globalization. Therefore temporal and spatial variability of climate, especially rainfall, is a major constraint to yield improvements, competitiveness and commercialization of rainfed crop, tree crops and livestock systems in most of the tropics. Management options should therefore start by focusing on reducing rainfall-induced risks.

Evidence is emerging that climate change is making the variability more intense, with increased frequency of extreme events such as drought, floods and hurricanes (IPCC, 2001). A recent study assessing rainfed cereal potential under different climate change scenarios, with varying total rainfall amounts, concluded that it is difficult to estimate the degree of regional impact. But most scenarios resulted in losses of rainfed production potential in the most vulnerable developing countries. In these countries, the loss of production area was estimated at 10–20%, with an approximate potential of 1–3 billion people affected in 2080 (IIASA, 2002). In particular, sub-Saharan Africa is estimated to lose 12% of the cultivation potential, mostly projected in the Sudan–Sahelian zone, which is already subject to high climatic variability and adverse crop conditions. Because of the risk associated with climate variability, smallholder farmers are generally and rationally keen to start by reducing risk of crop failure due to dry spells and drought before they consider investments in soil fertility, improved crop varieties and other yield-enhancing inputs (Hilhost and Muchena, 2000).

As the policy on water resource management for agriculture remains focused on irrigation, the framework for integrated water resource management at catchment and basin scales is primarily concentrated on allocation and management of blue water in rivers, groundwater and lakes. The evidence from the Comprehensive Assessment of Water for Food and Poverty Reduction indicated that the use of water for agriculture is larger than for irrigation, and there is an urgent need for a widening of the policy scope to include explicit strategies for water management in rainfed agriculture, including grazing and forest systems. However, what is needed is effective integration so as to have a focus on the investment options on water management across the continuum from rainfed to irrigated agriculture. The time is opportune to abandon the obsolete sectoral divide between irrigated and rainfed agriculture, which would place water resource management and planning more centrally in the policy domain of agriculture at large and not, as today, as a part of water resource policy (Molden *et al.*, 2007).

Furthermore, the current focus on water resource planning at the river basin scale is not appropriate for water management in rainfed agriculture, which overwhelmingly occurs on farms of <5 ha at the scale of small catchments, below the river basin scale. Therefore, the focus should be on water management at the catchment scale (or small tributary scale of a river basin), opening up much-needed investments in water resource management in rainfed agriculture also (Rockström *et al.*, 2007).

Small catchment

It is not surprising that most of the water management investments in rainfed agriculture since the late 1950s have focused on improved management of the rain that falls on the farmer's field. Soil and water conservation or *in-situ* water-harvesting systems form the logical entry point for improved water management in rainfed agriculture.

Since *in-situ* rainwater management strategies are often relatively cheap and can be applied literally on any piece of land, they should be optimized on any field before supply of water from external sources is considered. Established but incomplete evidence indicates that investing first in management of the local field water balance increases the likelihood of success in complementing the farming systems with supplemental irrigation systems based on rainwater harvesting, river-flow diversion or groundwater sources. This indicates that farmers who successfully manage to minimize losses of the rain that falls on the crop land are more likely to successfully adopt methods for dry spell mitigation. Tangible economic benefits to individuals through *in-situ* rainwater conservation were demonstrated while studying the drivers of collective action in successful watersheds (Wani *et al.*, 2003b; Sreedevi *et al.*, 2004). In policy and investment terms, this means that the focus should be on first tapping the *in-situ* potential prior to investing in external options.

Conservation agriculture[1] systems are one of the most important strategies to enhance soil productivity and moisture conservation. Non-inversion systems, where conventional ploughs are abandoned in favour of ripping, sub-soiling and no-tillage systems using direct planting techniques, combined with mulch management, builds organic matter and improves soil structure. Conservation agriculture is practised on approximately 40% of rainfed agriculture in the USA and has generated an agricultural revolution in several countries in Latin America (Derpsch, 1998, 2005; Landers *et al.*, 2001). Large-scale adoption of conservation agriculture systems is experienced among small-scale rainfed and irrigated farmers cultivating rice and wheat on the Indo-Gangetic plains in Asia (Hobbs and Gupta, 2002).

Conservation agriculture is of key importance in efforts to upgrade rainfed agriculture among the world's resource-poor farmers. It reduces traction requirements (by tractors or animal draught power), which saves money and is strategic from a gender perspective, as it generally gives women, particularly in female-headed households, a chance to carry out timely and effective tillage. A challenge is to find alternative strategies to manage weeds, particularly in poor farm households where herbicides are not an option. Furthermore, conservation agriculture can be practised on all agricultural land, i.e. there are no limitations related to the need for watershed areas and storage capacity for water harvesting. Conservation agriculture is a particularly important soil and water management strategy in hot tropical regions subject to water constraints. Soil inversion (using ploughs) in hot tropical environments leads to rapid oxidation of organic matter and increased soil erosion, which can be avoided using conservation agriculture practices. Some drawbacks with conservation agriculture might be the high initial costs of specialized planting equipment and the need for new management skills of the farmers. In addition, the use of pesticides might be necessary during the first years; however, after a few years the need normally declines to below the level of the original farming system.

Converting from ploughing to conservation agriculture using sub-soiling and ripping has resulted in major improvements in yield and water productivity in parts of semi-arid to dry subhumid East Africa, with a doubling of yields in good years, due to increased capture of rainwater (Box 1.4). Further increases in grain yield were achieved by applying manure. Compared with irrigation, these kinds of interventions can be implemented on all agricultural lands. Moreover, eastern and Southern Africa show a large potential to reduce labour needs and improve yields in smallholder rainfed agriculture with the adoption of conservation agriculture practices (Box 1.4). Yield improvements range from 20 to 120%, with rainwater productivity improving at 10–40%.

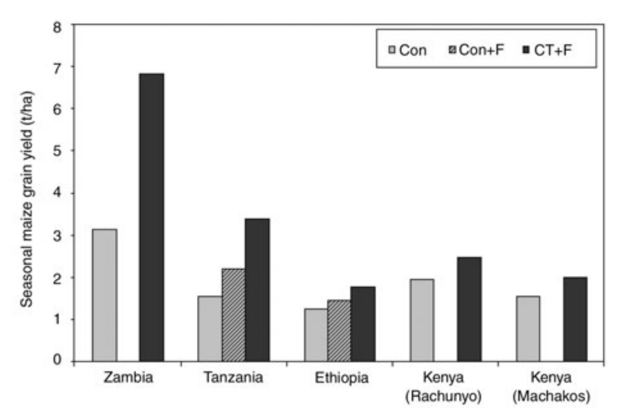
In-situ water-harvesting options also include techniques to concentrate run-off to plants, such as terracing, bunds, ridges, *khadins* and microbasins. The productivity of rain in arid environments can be substantially increased with appropriate water-harvesting techniques, which concentrate run-off to plants and trees (Box 1.5).

Shifting non-productive evaporation to productive transpiration

Rainwater use efficiency in agricultural systems in arid and SAT is 35–50%, and up to 50% of the rainwater falling on crop or pasture fields is lost as non-productive evaporation. This is a key window for improvement of green water productivity, as it entails shifting non-productive evaporation to productive transpiration, with no downstream water trade-off. This vapour shift (or transfer), where management of soil physical

Box 1.4. Conservation agriculture options in East Africa – a strategy for water and soil productivity improvement.

On-farm participatory trials on innovative conservation agriculture in semi-arid to dry subhumid Ethiopia, Kenya, Tanzania and Zambia indicate large potentials to substantially improve yields and rainwater productivity of staple food crops through conservation agriculture. Conservation agriculture involves the abandoning of soil inversion through conventional ploughing (generally mouldboard or disc ploughing), in favour of tillage systems with no turning and with minimum disturbance of the soil. Trials were carried out with farmers during 1999–2003, when yields increased significantly in all countries (see figure below). The conservation agriculture systems maximized rainfall infiltration into the soil, through ripping and sub-soiling. Draught animal traction requirements were reduced drastically (by at least 50%) and limited soil fertilization resources (manure and fertilizer) were applied along permanently ripped planting lines.



Maize yield improvements from conservation agricultural in on-farm trials in eastern and southern African countries. A conventional mouldboard ploughing system (Con) is compared with conventional ploughing with added fertilization (Con+F) and conservation agriculture using ripper and sub-soilers combined with fertilizer (CT+F).

conditions, soil fertility, crop varieties and agronomy are combined to shift the evaporative loss into useful transpiration by plants, is a particular opportunity in arid, semi-arid and dry subhumid regions (Rockström *et al.*, 2007).

Field measurements of rainfed grain yields and actual green water flows indicate that by doubling yields from 1 to 2 t/ha in semi-arid tropical agroecosystems, green water productivity may improve from approximately 3500 m^3/t to less than 2000 m^3/t. This is a result of the dynamic nature of water productivity improvements when moving from very low yields to higher yields. At low yields, crop water uptake is low and evaporative losses are high, as the leaf area coverage of the soil is low, which together result in high losses of rainwater as evaporation from soil. When yield levels increase, shading of soil improves, and when yields reach 4–5 t/ha and above, the canopy density is so high that the opportunity to reduce evaporation in favour of increased transpiration reduces, lowering the relative improvement of water productivity. This indicates that large opportunities for improving water productivity are found in low-yielding farming systems (Oweis *et al.*, 1998; Rockström, 2003), i.e. particularly in rainfed agriculture as compared with irrigated agriculture, where water productivity already is higher due to better yields.

Convergence and collective action

Convergence of actors and their actions at watershed level is needed to harness the synergies and to maximize the benefits through efficient and sustainable use of natural resources, to benefit

Box 1.5. Efficient use of *in-situ* water-harvesting techniques in arid regions.

Water-harvesting systems using small micro-basins are used to support plants and trees in arid and semi-arid environments. Small basins (*negarim*) have supported almond trees for over 17 years in the Muwaqqar area of Jordan, where the mean annual rainfall is 125 mm. The system has proved sustainable over a period of several years of drought (Oweis and Taimeh, 1996).

In the Mehasseh area of the Syrian steppe, with an average annual rainfall of 120 mm, the survival rate of rainfed shrubs is less than 10%, while those that were grown in micro-catchments had a survival rate of over 90%. Shrub survival rate can be improved between 70 and 90% with the introduction of water-harvesting interventions (semicircular bunds). In north-west Egypt, with an average annual rainfall of 130 mm, small water-harvesting basins with 200 m^2 watersheds support olive trees, and harvesting rainwater from greenhouse roofs can provide about 50% of the water required by vegetables grown inside the greenhouse (Somme *et al.*, 2004).

small and marginal farmers through increased productivity per unit of resource. We have missed out on large benefits of watershed programmes owing to a compartmental approach and there is an urgent need to bring in convergence as the benefits are manifold and it is win–win for all the stakeholders, including line departments involved in improving rural livelihoods.

New institutional mechanisms are also needed at district, state and national level to converge various watershed programmes implemented by several ministries and development agencies to enhance the impact and efficiency by overcoming duplicity and confusion. In 2005, the National Commission on Farmers recommended a holistic integrated watershed management approach, with focus on rainwater harvesting and improving soil health for sustainable development of drought-prone rainfed areas (Government of India, 2005). Recently, the Government of India has established the National Rain-fed Areas Authority (NRAA) with the mandate to converge various programmes for integrated development of rainfed agriculture in the country. These are welcome developments; however, it is just a beginning and lot more still needs to be done to provide institutional and policy support for development of rainfed areas. Thus, it has become increasingly clear that water management for rainfed agriculture requires a landscape perspective and involves cross-scale interactions from farm household scale to watershed/catchment scale.

Enhancing partnerships and institutional innovations through the consortium approach was the major impetus for harnessing the community watershed's potential to reduce households' poverty. The underlying element of the consortium approach adapted in ICRISAT-led community watersheds is engaging a range of actors with the locales as the primary implementing unit. Complex issues were effectively addressed by the joint efforts of ICRISAT and in collaboration with key partners, namely NARSs, non-governmental organizations (NGOs), government organizations, agricultural universities, community-based organizations and other private interest groups, with farm households as the key decision makers. In self-help groups (SHGs), such as village seed-banks, these were established not just to provide timely and quality seeds. This created the venue for receiving technical support and building the capacity of members such as women for the management of conservation and livelihood development activities. Incorporating a knowledge-based entry point in the approach led to the facilitation of rapport and at the same time enabled the community to take rational decisions for their own development. As demonstrated by ICRISAT, the strongest merit of the consortium approach is in the area of capacity building where farm households are not the sole beneficiaries. Researchers, development workers and students of various disciplines are also trained, and policy makers from the NARSs sensitized on the entire gamut of community watershed activities. Private–public partnership has provided the means for increased investments not only for enhancing productivity but also for building institutions as engines for people-led NRM.

From another aspect, the consortium approach has contributed to scaling through the nucleus–satellite scheme and building productive alliances for further research and technical backstopping. With cooperation, a balanced R&D programme was implemented rather than a 'purist model' of participation or mere adherence to government guidelines. A balanced R&D programme in community watersheds has encouraged scientific debate and at the same time promoted development through tangible economic benefits.

The other IARCs, such as the International Water Management Institute (IWMI), the International Livestock Research Institute (ILRI) and the World Wildlife Fund (WWF), have become allies because of common denominators like goal (poverty reduction) and subject (water resources). This not only maximized the use of resources but the problem situation in watersheds allowed for an integrated approach requiring the alliance of institutions and stakeholders. Similarly, the various networks such as the ASARECA and the Cereals and Legumes Asia Network (CLAN) have provided an added venue for exchange and collaboration. This led to a strong south–south partnership.

Discard artificial divide between irrigated and rainfed agriculture

Adopt an integrated water resource management approach in the watersheds by discarding the artificial divide between rainfed and irrigated agriculture. There is an urgent need to have sustainable water (rain-, ground- and surface water) use policies to ensure sustainable development. As described earlier, in the absence of suitable policies and mechanisms for sustainable use of groundwater resources, benefits of watershed programmes can easily be undone in a short period, with overexploitation of the augmented water resources. Cultivation of water-inefficient crops, like rice and sugarcane, using groundwater in watersheds needs to be controlled through suitable incentive mechanisms for rainfed irrigated crops and policy to stop cultivation of high-water-requiring crops.

Business model

Watersheds should be developed as a business model through public–private partnership using principles of market-led diversification using high-value crops, a value-chain approach and a livelihood approach rather than only a soil and water conservation approach. Strengths of rainfed areas using available water resources efficiently through involvement of private entrepreneurs and value addition can be harnessed by linking small and marginal farmers to markets through a public–private partnership business model for watershed management.

Watershed approach for rainfed areas

In several countries, central and state governments have emphasized management of rainfed agriculture under various programmes. Important efforts, for example, have been made under the watershed development programmes in India. Originally, these programmes were implemented by different ministries such as the Ministry of Agriculture, the Ministry of Rural Development and the Ministry of Forestry, causing difficulties for integrated water management. Recently, steps were taken to unify the programme according to the 'Hariyali Guidelines' (Wani *et al.*, 2006a) and as per the common watershed guidelines developed by NRAA (Government of India, 2008).

Meta-analysis

Detailed meta-analysis of 311 watershed case studies in India revealed that watershed programmes are silently revolutionizing rainfed areas, with positive impacts (benefit–cost ratio of 1:2.14, internal rate of return of 22%, cropping intensity increased by 63%, irrigated areas increased by 34%, run-off reduced by 13% and employment increased by 181 person-days/year/ha) (Joshi *et al.*, 2005). However, 65% of the watersheds were performing below average as they lacked community participation, programmes were supply driven, equity and sustainability issues were eluding and a compartmental approach was adopted (Joshi *et al.*, 2005) (Table 1.9). Based on the knowledge gained from the meta-analysis and earlier on-farm watersheds, ICRISAT, in partnership with NARSs, developed and evaluated an innovative farmers' participatory integrated watershed consortium model for increasing agricultural productivity and later for improving rural livelihoods (Wani *et al.*, 2003b).

Table 1.9. Benefits of watersheds – summary of meta-analysis.

Indicator	Particulars	Unit	No. of studies	Mean	Mode	Median	Min	Max	t- value
Efficiency	Benefit–cost ratio	Ratio	128	2.14	1.70	1.81	0.82	7.06	21.25
	IRR[a]	%	40	22.04	19.00	16.90	1.68	94.00	6.54
Equity	Employment	person-days/ha/year	39	181.50	75.00	127.00	11.00	900.00	6.74
Sustainability (%)	Irrigated area	%	97	33.56	52.00	26.00	1.37	156.03	11.77
	Cropping intensity	%	115	63.51	80.00	41.00	10.00	200.00	12.65
	Rate of run-off	%	36	–13.00	–33.00	–11.00	–1.30	–50.00	6.78
	Soil loss	t/ha/year	51	–0.82	–0.91	–0.88	–0.11	–0.99	39.29

[a] IRR = internal rate of return.

Thus, it has become increasingly clear that water management for rainfed agriculture requires a landscape perspective, and involves cross-scale interactions from farm household scale to watershed/catchment scale and upstream–downstream linkages.

Pilot-scale model community watershed

Based on detailed studies and synthesis of the results, impacts, shortcomings and knowledge gained from a large number of watershed programmes and on-farm experiences, an ICRISAT-led consortium developed an innovative farmers' participatory consortium model for integrated watershed management (Wani *et al.*, 2002, 2003b,c). ICRISAT has launched several pilot-scale models of community watersheds based on the knowledge gained over 25 years of strategic and on-farm development research using CGIAR priorities as its guide. The ICRISAT-led watershed espouses the IGNRM approach, where activities are implemented at landscape level. Research and development interventions at landscape level were conducted at benchmark sites representing the different agroecoregions of the SAT. The entire process revolves around the four Es (empowerment, equity, efficiency and environment), which are addressed by adopting specific strategies prescribed by the four Cs (consortium, convergence, cooperation and capacity building). The consortium strategy brings together institutions from the scientific, non-government, government and farmers groups for knowledge management. Convergence allows integration and negotiation of ideas among actors. Cooperation enjoins all stakeholders to harness the power of collective actions. Capacity building engages in empowerment for sustainability (Wani *et al.*, 2003a).

The important components of the new model, which are distinct from the earlier ones, are:

- Collective action by farmers and participation from the beginning through cooperative and collegiate mode in place of contractual mode.
- Integrated water resource management and holistic system approach through convergence for improving livelihoods as against traditional compartmental approach.
- A consortium of institutions for technical backstopping.
- Knowledge-based entry point to build rapport with community and enhanced participation of farmers and landless people through empowerment.
- Tangible economic benefits to individuals through on-farm interventions enhancing efficiency of conserved soil and water resources.
- Low-cost and environment-friendly soil and water conservation measures throughout the toposequence for more equitable benefits to a large number of farmers.
- Income-generating activities for the landless and women through allied sector activities and rehabilitation of wastelands for improved livelihoods and protecting the environment.

Integrated watershed management deals with conservation and efficient use of rainwater, groundwater, land and other natural resources for increasing agricultural productivity and improving livelihoods. Watershed management is used as an entry point to increase cropping intensity and also to rehabilitate degraded lands in the catchments in order to increase productivity, enhance biodiversity, increase incomes and improve livelihoods. Such an approach demands integrated and holistic solutions from seed to final produce, with involvement of various institutions and actors with diversified expertise varying across technical, social, financial, market and human resource development, and so on. The programme outputs are tuned to reduce poverty, minimize land degradation, increase productivity and production, and build communities' resilience to shocks due to natural calamities such as drought and flood as well as the climate variability due to global warming.

Multiple benefits and impacts

Through the use of new science tools (i.e. remote sensing, geographical information systems (GIS) and simulation modelling) along with an understanding of the entire food production–utilization system (i.e. food quality and market) and genuine involvement of stakeholders, ICRISAT-led watersheds effected remarkable impacts on SAT resource-poor farm households.

Reducing rural poverty – in the watershed communities, this is evident in the transformation of their economies. The ICRISAT model ensured improved productivity with the adoption of cost-efficient water-harvesting structures (WHS) as an entry point for improving livelihoods. Crop intensification and diversification with high-value crops is one leading example that allowed households to achieve production of basic staples and surplus for modest incomes. The model has provision for improving the capacity of farm households through training and networking and for improved livelihood-enhanced participation, especially of the most vulnerable groups such as women and the landless. For example, the SHGs common in the watershed villages of India and an improved initiative in China provide income and empowerment of women. The environmental clubs, whose conceptualization is traced from Bundi watershed in Rajasthan, India, inculcated environmental protection, sanitation and hygiene among the children.

Building on social capital made the huge difference in addressing rural poverty of watershed communities. This is evident in the case of Kothapally watershed in Andhra Pradesh, India. Today, it is a prosperous village on the path of long-term sustainability and has become a beacon for science-led rural development. In 2001, the average village income from agriculture, livestock and non-farming sources was US$945 compared with the neighbouring non-watershed village income of US$613 (Fig. 1.9). The villagers proudly professed: 'We did not face any difficulty for water even during the drought year of 2002. When surrounding villages had no drinking water, our wells had sufficient water.'

To date, the village prides itself on households owning five tractors, seven lorries and 30 autorickshaws. People from surrounding villages come to Kothapally for on-farm employment. With more training on livelihood and enterprise development, migration is bound to cease. Between 2000 and 2003, investments in new livelihood enterprises such as a seed oil mill, a tree nursery and worm composting increased average income by 77% in Powerguda, a tribal village in Andhra Pradesh.

Crop–livestock integration is another facet harnessed for poverty reduction. The Lucheba watershed, Guizhou province of southern China, has transformed its economy through modest injection of capital-allied contributions of labour and finance, to create basic infrastructures such as access to roads and drinking water supply. With technical support from the consortium, the farming system was intensified from rice and rape seed to tending livestock (pig raising) and growing horticultural crops (fruit trees such as *Ziziphus*; vegetables such as beans, peas and sweet potato) and groundnuts. In forage production, wild buckwheat was specifically important as an alley crop as it was a good forage grass for pigs. This cropping technology was also effective in controlling erosion and increasing farm income in sloping lands. This holds true in many watersheds of India, where the improvement in fodder production has intensified livestock activities such as breed improvement (artificial insemination and natural means) and livestock centre/health camp establishment (Wani *et al.*, 2006b).

In Tad Fa and Wang Chai watersheds in Thailand, there was a 45% increase in farm income within 3 years. Farmers earned an average net income of US$1195 per cropping season. A complete turnaround in the livelihood system of farm households was inevitable in ICRISAT-led watersheds.

Increasing crop productivity – this is a common objective in all the watershed programmes, and the enhanced crop productivity is achieved after the implementation of soil and water conservation practices along with appropriate crop and nutrient management. For example, the implementation of improved crop management technology in the benchmark watersheds of Andhra Pradesh increased the maize yield by two and a half times (Table 1.6) and sorghum yield by threefold (Wani *et al.*, 2006a). Overall, in the 65 community watersheds (each measuring approximately 500 ha), implementing best-bet practices resulted in significant yield advantages in sorghum (35–270%), maize (30–174%), pearl millet (72–242%), groundnut (28–179%), sole pigeonpea (97–204%) and intercropped pigeonpea (40–110%). In Thanh Ha watershed of Vietnam, yields of soybean, groundnut and mung bean increased by threefold to fourfold (2.8–3.5 t/ha) as compared with baseline yields (0.5–1.0 t/ha), reducing the yield gap between potential farmers' yields. A reduction in nitrogen fertilizer (90–120 kg urea per ha) by 38% increased maize yield by 18%. In Tad Fa watershed in north-eastern Thailand, maize yield increased by 27–34% with improved crop management.

Improving water availability – in the watersheds this was attributed to efficient management of rainwater and *in-situ* conservation, establishment of WHS and improved groundwater levels. Findings in most of the watershed sites reveal that open wells located near WHS have significantly higher water levels compared with those away from the WHS. Even after the rainy season, the water level in wells nearer to WHS sustained good groundwater yield. In the various watersheds of India such as Lalatora (in Madhya Pradesh), the treated area registered a groundwater level rise of 7.3 m. At Bundi, Rajasthan, the average rise was 5.7 m and the irrigated area increased from 207 to 343 ha. In Kothapally watershed in Andhra Pradesh, the groundwater level rise was 4.2 m in open wells (Fig. 1.11). The various WHS resulted in an additional groundwater recharge per year of approximately 428,000 m^3 on average. With this improvement in groundwater availability, the supply of clean drinking water was guaranteed. In Lucheba watershed in China, a drinking water project, which constitutes a water storage tank and pipelines to farm households, was a joint effort of the community and the watershed project. This solved the drinking water problem for 62 households and more than 300 livestock. Earlier every farmer's household used to spend 2–3 h per day fetching drinking water. This was the main motivation for the excellent farmers' participation in the project. On the other hand, collective pumping out of well water established an efficient water distribution system and enabled the farmers' group to earn more income by growing watermelon, with reduced drudgery as women used to carry water on their heads from a long distance. Pumping of water from the river as a means of irrigating watermelon has provided maximum income for households in Thanh Ha watershed (in Vietnam) (Wani *et al.*, 2006b).

Supplemental irrigation – this can play a very important role in reducing the risk of crop failures and in optimizing the productivity in the SAT. In these regions, there is good potential for delivering excess rainwater to storage structures or groundwater, because even under improved systems there is loss of 12–30% of the rainfall as run-off. Striking results were recorded from supplemental irrigation on crop yields in ICRISAT benchmark watersheds in Madhya Pradesh. On-farm studies made during the 2000–2003 post-rainy seasons showed that chickpea yield (1.25 t/ha) increased by 127% over the control yield (0.55 t/ha), and groundnut pod yield (1.3 t/ha) increased by 59% over the control yield (0.82 t/ha) by application of two supplemental irrigations of 40 mm. Similar yield responses in mung bean and chickpea crops were obtained from supplemental irrigation at the ICRISAT centre in Patancheru. Our results showed that crops on light-textured soils such as alfisols respond better with supplemental irrigation. Clearly, there is potential to enhance productivity and reduce the risks of crop failures through application of harvested water through supplemental irrigation at the critical stage of the crop (for more details *see* Chapter 11, this volume).

Sustaining development and protecting the environment – these are the two-pronged

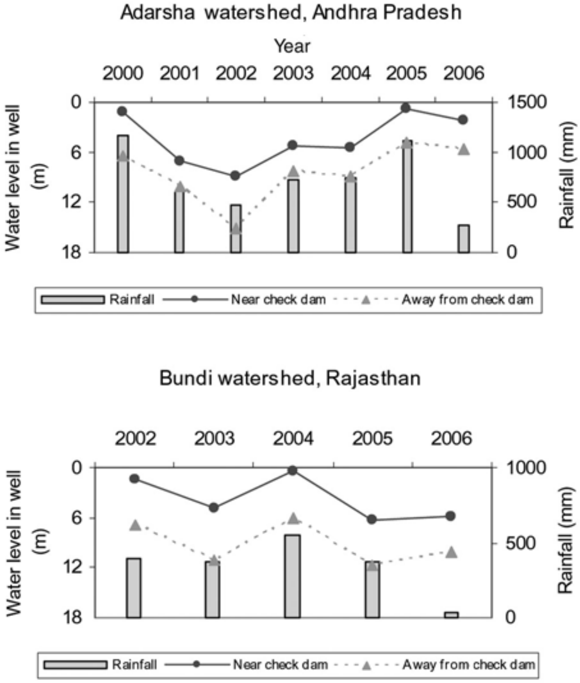


Fig. 1.11. The impact of watershed interventions on groundwater levels at two benchmark sites in India. (Note: estimated additional groundwater recharge due to watershed interventions is 675,000 m^3/year in Bundi watershed and 427,800 m^3/year in Adarsha watershed.)

achievements of the watersheds. The effectiveness of improved watershed technologies was evident in reducing run-off volume, peak run-off rate and soil loss and improving groundwater recharge. This is particularly significant in Tad Fa watershed, where interventions such as contour cultivation at mid-slopes, vegetative bunds planted with *Vetiver*, fruit trees grown on steep slopes and relay cropping with rice bean reduced seasonal run-off to less than half (194 mm) and soil loss to less than one-seventh (4.21 t/ha) as compared with the conventional system (473 mm run-off and soil loss 31.2 t/ha). This holds true with peak run-off rate, where the reduction is approximately one-third (Table 1.10).

A large number of fields (80–100%) in the SAT were found to be severely deficient in zinc, boron and sulfur as well as nitrogen and phosphorus. Amendment of soils with the deficient micro- and secondary nutrients increased crop yields by 30–70%, resulting in overall increase in water and nutrient use efficiency. Introduction of integrated pest management (IPM) and improved cropping systems decreased the use of pesticides worth US$44 to 66 per ha. Crop rotation using legumes in Wang Chai watershed (Thailand) substantially reduced the nitrogen requirement for rainfed sugarcane. The IPM practices, which brought into use local knowledge using insect traps of molasses, light traps and tobacco waste, led to extensive vegetable production in Xiaoxingcun (China) and Wang Chai (Thailand) watersheds.

Improved land and water management practices along with integrated nutrient management comprising application of inorganic fertilizers and organic amendments (such as crop residues, vermicompost, farm manures and *Gliricidia* loppings) as well as crop diversification with legumes not only enhanced productivity but also improved soil quality. Increased carbon sequestration of 7.4 t/ha in 24 years was observed with improved management options in a long-term

Table 1.10. Seasonal rainfall, run-off and soil loss from different benchmark watersheds in India and Thailand.

Watershed	Seasonal rainfall (mm)	Run-off (mm)		Soil loss (t/ha)	
		Treated	Untreated	Treated	Untreated
Tad Fa (Khon Kaen, NE Thailand)	1284	169	364	4.21	31.2
Kothapally (Andhra Pradesh, India)	743	44	67	0.82	1.9
Ringnodia (Madhya Pradesh, India)	764	21	66	0.75	2.2
Lalatora (Madhya Pradesh, India)	1046	70	273	0.63	3.2

watershed experiment at ICRISAT. By adopting fuel-switch for carbon, women SHGs in Powerguda (a remote village of Andhra Pradesh, India) have pioneered the sale of carbon units (147 t CO_2 C) to the World Bank from their 4500 *Pongamia* trees, seeds of which are collected for producing saplings for distribution/promotion of biodiesel plantation. Normalized difference vegetation index (NDVI) estimation from the satellite images showed that within 4 years vegetation cover could increase by 35% in Kothapally. The IGNRM options in the watersheds reduced loss of NO_3-N in run-off water (8 versus 14 kg nitrogen per ha). Introduction of IPM in cotton and pigeonpea substantially reduced the number of chemical insecticidal sprays during the season and thus reduced the pollution of water bodies with harmful chemicals. Reduced run-off and erosion reduced risk of downstream flooding and siltation of water bodies, which directly improved environmental quality in the watersheds (Pathak *et al.*, 2005; Sahrawat *et al.*, 2005; Wani *et al.*, 2005).

Conserving biodiversity – in the watersheds, this was engendered through participatory NRM. The index of surface percentage of crops (ISPC), crop agrobiodiversity factor (CAF), and surface variability of main crops changed as a result of integrated watershed management interventions. Pronounced agrobiodiversity impacts were observed in Kothapally watershed, where farmers now grow 22 crops in a season with a remarkable shift in cropping pattern from cotton (200 ha in 1998 to 100 ha in 2002) to a maize/pigeonpea intercrop system (40 ha in 1998 to 180 ha in 2002), thereby changing the CAF from 0.41 in 1998 to 0.73 in 2002. In Thanh Ha, Vietnam, the CAF changed from 0.25 in 1998 to 0.6 in 2002 with the introduction of legumes. Similarly, rehabilitation of the common property resource land in Bundi watershed through the collective action of the community ensured the availability of fodder for all the households and income of US$1670 per year for the SHG through sale of grass to the surrounding villages. Above-ground diversity of plants (54 plant species belonging to 35 families) as well as below-ground diversity of microorganisms (21 bacterial isolates, 31 fungal species and 1.6 times higher biomass C) was evident in rehabilitated CPR as compared with the degraded CPR land (9 plant species, 18 bacterial isolates and 20 fungal isolates, of which 75% belong to the *Aspergillus* genus) (Wani *et al.*, 2005).

Promoting NRM at the landscape level – this enabled the study of impact factors of NRM, such as sustainability of production, soil and water quality, and other environment resources have been looked at from a landscape perspective. This accounts for some successes in addressing concerns on equity issues such as benefits for the poorest people, for example the landless, who are unable to take advantage of improved soil/water conditions, and expansion of water-intensive crops triggering renewed water stress. These remain as legitimate challenges to a holistic thinking, which can be better unravelled from a landscape scale. To date, the articulation of this recognition is to be seen in policy recommendations for serious attention to capacity building and not just for planning activities.

Equal importance was given to on-site and off-site impacts. The effects of water conservation at the upper ridge to downstream communities were factored in. Water-harvesting structures, specifically the rehabilitation of the *nala* (drain) bund at the upper portion in Bundi watershed (Rajasthan), allowed irrigation of 6.6 ha at the downstream part. Another case is the Aniyala watershed, located at the lower toposequence of Rajasamadhiyala watershed in Gujarat, India. Excess water flows of the 21 WHS in Rajasamadhiyala cascades into Aniyala. This increased groundwater recharge by 25% and improved the groundwater source by 50% in a normal rainfall year. Because of this, there was an increase in crop production by 25–30% (Sreedevi *et al.*, 2006). The quality and number of livestock in the village improved because of water and fodder availability. Off-site effects of watershed-specific equity issues is one area that needs to be strengthened for enhanced impact.

Scaling-up

Factors such as low soil fertility, inappropriate soil and water management practices causing land degradation, lack of improved varieties, pest and disease attack, resource-poor farmers, declining land:man ratio and poor rural communities, who are unable to meet even minimum standards of health and nutrition, add to the burgeoning problem of rural poverty (Wani *et al.*, 2001). The adoption of the new paradigm in rainfed agriculture has shown that with proper management of natural resources the system's productivity can be enhanced and poverty can be reduced without causing further degradation of the natural resource base. The scaling-up of these innovations has been attempted in Andhra Pradesh, India, through the Andhra Pradesh Rural Livelihoods Programme (APRLP).

The approach of the APRLP puts the people living in the watershed at the centre of development and involves not only conservation of soil and water but also the efficient and sustainable use of natural resources to improve the livelihoods of everyone living in the watershed, with a special emphasis on the marginalized groups of people, such as those with little or no land, women and the poorest of the community (APRLP, 2006, 2007). The project has adopted a participatory 'Sustainable Rural Livelihoods' strategy (SRL), which is based on an analysis of the capital assets (physical, social, human, natural and financial) from which the rural poor derive their livelihoods. The approach also takes into consideration the vulnerability and risks that people face, local policies and constraints and the institutional environment. Since sustainable livelihoods approaches are based on empowerment, gender and equity have been mainstreamed in all the activities of the project. It is important to note that the APRLP is not a stand-alone project; it works within the watershed programme to bring about change which will ensure that the poorest people benefit from watershed programme interventions as well as gain access to new livelihood opportunities. The APRLP promoted activities which are off-farm and non-farm as well as those which are land based, building on what people already do and enhancing the skills they have. In order to achieve sustained development, the APRLP followed a participatory approach that ensured demand-driven planning and implementation and promoted convergence with other rural development programmes, government schemes and other government line departments in the state as well as other institutions and programmes run by NGOs.

Apart from the APRLP there are also other efforts to scale up these innovations, particularly the consortium model of integrated watershed management with backstopping and technical support from ICRISAT. The major efforts are the Sujala watershed programme in Karnataka, India, supported by the World Bank; watershed programmes in three districts of Madhya Pradesh and Rajasthan, with support from the Sir Dorabji Tata Trust, Mumbai, India; and in four countries in Asia (India, Thailand, Vietnam and China), with the support of the Asian Development Bank (ADB), the Philippines (for more details on upscaling strategies for IWM, see Chapter 12, this volume).

Conclusions

Rural development through sustainable management of land and water resources gives a plausible solution for alleviating rural poverty and improving the livelihoods of the rural poor. In an effective convergence mode for improving the rural livelihoods in the target districts, with watersheds as the operational units, a holistic integrated systems approach by drawing attention to the past experiences, existing opportunities and skills, and supported partnerships can enable change and improve the livelihoods of the rural poor. The well-being of the rural poor depends on fostering their fair and equitable access to productive resources. The rationale behind convergence through watersheds has been that these watersheds help in 'cross-learning' and drawing on a wide range of experiences from different sectors. A significant conclusion is that there should be a balance between attending to needs and priorities of rural livelihoods and enhancing positive directions of change by building effective and sustainable partnerships. Based on the experience and performance of the existing integrated community watersheds in different socio-economic environments, appropriate exit strategies, which include proper sequencing of interventions, building up of financial, technical and organizational capacity of local communities to internalize and sustain interventions, and the requirement for any minimal external technical and organizational support need to be identified.

Note

[1] Conservation agriculture, often defined as conservation tillage or conservation farming, includes tillage systems with no inversion of soil, i.e. without conventional ploughing, and ranges from no-tillage to minimum tillage and tillage systems aimed at opening the soil for rainfall capture without inversion. These systems include crop rotations and a mulch cover, which according to the convention should allow at least an average 30% cover of the soil throughout the year. For many farming systems in arid, semi-arid and dry subhumid tropical regions a permanent mulch cover is difficult to sustain. Despite this difficulty, conservation agriculture systems, often adopted as a strategy for *in-situ* water harvesting, show much promise, even though difficulties with weed management are a more prominent challenge than when securing a mulch cover. The Comprehensive Assessment has chosen to adopt a wide definition of conservation agriculture focused on non-inversion tillage for improvement of soil and water management (including sub-soiling, ripping, pitting and no-till systems).

References

Agarwal, A. (2000) Drought? Try capturing the rain. Briefing paper for members of parliament and state legislatures – an occasional paper from the Centre for Science and Environment (CSE), New Delhi, India.

APRLP (Andhra Pradesh Rural Livelihoods Programme) (2006) Building livelihoods: the APRLP experience. APRLP, Government of Andhra Pradesh, India.

APRLP (Andhra Pradesh Rural Livelihoods Programme) (2007) Andhra Pradesh rural livelihoods project: an overview. APRLP, Government of Andhra Pradesh, India.

Barron, J., Rockström, J., Gichuki, F. and Hatibu, N. (2003) Dry spell analysis and maize yields for two semi-arid locations in East Africa. *Agriculture for Meteorology* 117(1–2), 23–37.

Bossio, D., Critchley, W., Geheb, K., van Lynden, G. and Mati, B. (2007) Conserving land – protecting water. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 551–584.

Commission for Africa (2005) Commission for Africa report: March 2005 (accessed in May 2005) (http://213.225.14043/english/report/introduction.htm).

Derpsch, R. (1998) Historical review of no-tillage cultivation of crops. In: Benites, J., Chuma, E., Fowler, R., Kienzle, J., Molapong, K., Manu, J., Nyagumbo, I., Steiner, K. and van Veenhuizen, R. (eds) *Conservation Tillage for Sustainable Agriculture*. Proceedings from an international workshop, 22–27 June 1997, Harare. Part II (Annexes). Deutsche Gesellschaft, GTZ, Eschborn, Germany, pp. 205–218.

Derpsch, R. (2005) The extent of conservation agriculture adoption worldwide: implications and impact. Keynote paper at the 3rd World Congress on Conservation Agriculture, 3–7 Oct 2005, Nairobi, Kenya, organized by RELMA/ICRAF, Nairobi, Kenya.

DFID (2002) Better livelihoods for poor people: the role of agriculture. Issues paper, Department for International Development (DFID), London, UK.

Dimes, J.P. (2005) Application of APSIM to evaluate crop improvement technologies for enhanced water use efficiency in Zimbabwe's SAT. In: Pala, M., Beukes, D.J., Dimes, J.P. and Myers, R.J.K. (eds) *Management for Improved Water Use Efficiency in the Dry Areas of Africa and West Asia*. Proceedings of a workshop organized by Optimizing Soils Water Use (OSWU) Consortium, April 2002, Ankara, Turkey. International Centre for Agricultural Research in the Dry Areas (ICARDA), Aleppo Syria; and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India, pp. 203–211.

Dimes, J., Twomlow, S., Rusike, J., Gerard, B., Tabo, R., Freeman, A. and Keatinge, J.D.H. (2005) Increasing research impacts through low-cost soil fertility management options for Africa's drought-prone areas. In: Omanya, G.O. and Pasternak, D (eds) *Sustainable Agriculture Systems for the Drylands*. Proceedings of the International Symposium for Sustainable Dryland Agriculture Systems, 2–5 December 2003, Niamey, Niger. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Niamey, Niger, pp. 82–92.

Drechsel, P., Giordano, M. and Gyiele, L. (2004) Valuing nutrition in soil and water: concepts and techniques with examples from IWMI studies in developing world. IWMI Research Paper 82. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Falkenmark, M. (1986) Fresh water – time for a modified approach. *Ambio* 15(4), 192–200.

Falkenmark, M. and Rockström, J. (2004) *Balancing Water for Humans and Nature: the New Approach in Ecohydrology*. Earthscan, London, UK.

FAO (2002) Agriculture: towards 2015/30. Technical Interim Report. (http://www.fao.org/es/esd/at2015/toc-e.htm).

FAO/IIASA (2000) Global agroecological zones (Global-AEZ) CD-Rom. Downloaded from http://www.iiasa.ac.at/Research/LUC/GAEZ in February 2006.

FAOSTAT (2005) http://faostat.fao.org/ (last accessed November 2005).

Glantz, M.H. (1994) *Drought Follows the Plough: Cultivating Marginal Areas*. Cambridge University Press, Cambridge, UK.

Government of India (2005) *Serving Farmers and Saving Farming – 2006: Year of Agricultural Renewal*. Third Report. December 2005. National Commission on Farmers, Ministry of Agriculture, Government of India, New Delhi, India.

Government of India (2008) Common guidelines for watershed development projects. National Rain-fed Area Authority (NRAA), Ministry of Land Resources, Government of Andhra Pradesh, India.

Heinrich, G.M. and Rusike, J. (2003) Increasing productivity final report SMIP IR1.2. SADC/ICRISAT sorghum and millet improvement program (SMIP). Final review and reporting workshop: achievements and future directions for sorghum and millet R&D in Southern Africa, 25–26 November 2003, Bulawayo, Zimbabwe.

Hilhost, T. and Muchena, F. (2000) *Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems*. International Institute for Environment and Development, London, UK.

Hobbs, P.R. and Gupta, R.K. (2002) Rice–wheat cropping systems in the Indo-Gangetic plains: issues of water productivity in relation to new resource conserving technologies. In: Kijne, J.W. (ed.) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 239–253.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2005) Identifying systems for carbon sequestration and increased productivity in semi-arid tropical environments. A project completion report funded by National Agricultural Technology Project, Indian Council of Agricultural Research.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2006) *ICRISAT's Vision and Strategy to 2015*. ICRISAT, Patancheru, Andhra Pradesh, India.

IFAD (International Fund for Agricultural Development) (2001) *Rural Poverty Report 2001: the Challenge of Ending Rural Poverty*. Oxford University Press, Oxford, UK.

IFDC (2006) Agricultural production and soil nutrient mining in Africa: implications for resource conservation and policy development. IFDC Technical Bulletin. IFDC, Alabama, USA.

IIASA (2002) Climate change and agricultural vulnerability. Special report for the UN World Summit on Sustainable Development, Johannesburg 2002 (http://www.iiasa.ac.at/Research/LUC/JB-Report.pdf).

Inter Academy Council (2004) Realizing the promise and potential of African agriculture: science and technology strategies for improving agricultural productivity and food security in Africa. IAC Secretariat, Amsterdam, the Netherlands. http://www.interacademycouncil.net (accessed in May 2005).

IPCC (2001) *Intergovernmental Panel on Climate Change, Third Assessment Report.* Cambridge University Press, Cambridge, UK. http://www.ipcc.ch.

Irz, X. and Roe, T. (2000) Can the world feed itself? Some insights from growth theory. *Agrekon* 39(3), 513–528.

Johnston, D.G. and Mellor, J.W. (1961) The role of agriculture in economic development. *American Economic Review* 51(4), 566–593.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. (2005) Meta-analysis to assess impact of watershed program and people's participation. Comprehensive Assessment Research Report 8. Comprehensive Assessment Secretariat (IWMI), Colombo, Sri Lanka.

Kassam, A.H., Gregersen, H.M., Ferres, E., Javier, Q., Harwood, R.R., de Jancrym, A. and Cernea, M.M. (2004) A framework for enhancing and guarding the relevance and quality of science: The case of the CGIAR. *Experimental Agriculture* 40, 1–21.

Kesava Rao, A.V.R., Wani, S.P., Singh, P., Irshad Ahmed, M. and Srinivas, K. (2007) Agroclimatic characterization of APRLP–ICRISAT nucleus watersheds in Nalgonda, Mahabubnagar and Kurnool districts. *Journal of SAT Agricultural Research* (an e-journal published by ICRISAT) 3(1), 1– 55.

Koning, N. (2002) Should Africa protect its farmers to revitalise its economy? Working Paper North–South Centre, Wageningen University and Research Centre, Wageningen, the Netherlands.

Landers, J.N., Mattana Saturnio, H., de Freitas, P.L. and Trecenti, R. (2001) Experiences with farmer clubs in dissemination of zero tillage in tropical Brazil. In: García-Torres, L., Benites, J. and Martínez-Vilela, A. (eds) *Conservation Agriculture, a Worldwide Challenge.* Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 71–76.

Molden, D. (ed.) (2007) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture.* Earthscan, London and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 1–39.

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., Sadoff, C. and Finlayson, M.C. (2007) Trends in water and agricultural development In: Molden, D. (ed.) *Water for Food: Water for Life – a Comprehensive Assessment of Water Management in Agriculture.* International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 57–89.

Mwale, F. (2003) Drought impact on maize production in Malawi. Unesco-IHE Report. Delft, the Netherlands.

Narongsak, S., Precha, C., Chanvid, L., Somchai, T., Suppachai, A., Arun, P., Pranee, S., Thommasak, S., Aran, P., Banyong, T., Sawaeng, R. and Rego T.J. (2003) Improving management of natural resources for sustainable rainfed agriculture in north-eastern Thailand. In: Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, T.J. (eds) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia.* Proceedings of the ADB–ICRISAT–IWMI Project Review and Planning Meeting, 10–14 December 2001, Hanoi, Vietnam, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India, pp. 123–133.

Ncube, B., Dimes, J.P., Twomlow, S.J., Mupangwa, W. and Giller, K.E. (2006) Raising the productivity of smallholder farms under semi-arid conditions by use of small doses of manure and nitrogen: a case study of participatory research. *Nutrient Cycling in Agroecosystems* 77, 53–67.

Oweis, T. and Hachum, A. (2001) Reducing peak supplemental irrigation demand by extending sowing dates. *Agricultural Water Management* 50, 109–123.

Oweis, T. and Taimeh, A. (1996) Evaluation of small basin water harvesting systems in the arid region of Jordan. *Water Resources Management* 10, 21–34.

Oweis, T., Pala, M. and Ryan, J. (1998) Stabilizing rain-fed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. *Agronomy Journal* 90, 672–681.

Pathak, P., Sahrawat, K.L., Rego, T.J. and Wani, S.P. (2005) Measurable biophysical indicators for impact assessment: changes in soil quality. In: Shiferaw, B., Freeman, H.A. and Swinton, S.M. (eds) *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts.* CAB International, Wallingford, UK, pp. 53–74.

Pathak, P., Wani, S.P. and Sudi, R. (2006) Gully control in SAT watersheds. *Global Theme on Agroecosystems Report No. 15.* International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Ramankutty, N., Foley, J.A. and Olejniczak, N.J. (2002) People and land: changes in global population and croplands during the 20th century. *Ambio* 31(3), 251–257.

Rego, T.J., Wani, S.P., Sahrawat, K.L. and Pardhasardhy, G. (2005) Macro-benefits from boron, zinc, and sulphur application in Indian SAT: a step for grey to green revolution in agriculture. *Global Theme on*

Agroecosystems Report No. 16. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Rockström, J. (2003) Water for food and nature in the tropics: vapour shift in rain-fed agriculture. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences* 358(1440), 1997–2009.

Rockström, J. and Falkenmark, M. (2000) Semiarid crop production from a hydrological perspective: gap between potential and actual yields. *Critical Reviews in Plant Science* 19(4), 319–346.

Rockström, J., Hatibu, N., Oweis, T. and Wani, S.P. (2007) Managing water in rain-fed agriculture. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–348.

Rosegrant, M., Ximing, C., Cline, S. and Nakagawa, N. (2002) The role of rain-fed agriculture in the future of global food production. EPTD Discussion Paper No. 90, Environment and Production Technology Division, IFPRI, Washington, DC, USA (http://www.ifpri.org/divs/eptd/dp/papers/eptdp90.pdf).

Rusike, J., Twomlow, S.J., Freeman, H.A. and Heinrich, G.M. (2006) Does farmer participatory research matter for improved soil fertility technology development and dissemination in Southern Africa? *International Journal of Agricultural Sustainability* 4(3), 176–192.

Ryan, J.G. and Spencer, D.C. (2001) *Challenges and Opportunities Shaping the Future of the Semi-Arid Tropics and their Implications*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Sahrawat, K.L., Bhattacharyya, T., Wani, S.P., Ray, S.K., Pal, D.K. and Padmaja, K.V. (2005) Long-term lowland rice and arable cropping effects on carbon and nitrogen status of some semi-arid tropical soils. *Current Science* 89(12), 2159–2163.

Sahrawat, K.L., Wani, S.P., Rego, T.J., Pardhasaradhi, G. and Murthy, K.V.S. (2007) Widespread deficiencies of sulphur, boron and zinc in dryland soils of the Indian semi-arid tropics. *Current Science* 93(10), 1–6.

SEI (Stockholm Environment Institute) (2005) Sustainable pathways to attain the millennium development goals – assessing the role of water, energy and sanitation. Document prepared for the UN World Summit, 14 September 2005, New York, USA SEI, Stockholm, Sweden. (http://www.sei.se/mdg.htm).

Snapp, S. and Heong, K.L. (2003) Scaling up and out. In: Pound, B., Snapp, S., McDougall, C. and Braun, A. (eds) *Managing Natural Resources for Sustainable Livelihoods: Uniting Science and Participation*. IDRC and Earthscan Books, London, UK, pp. 67–83.

Somme, G., Oweis, T., Abdulal, Q., Bruggeman, A. and Ali, A. (2004) Micro-catchment water harvesting for improved vegetative cover in the Syrian badia. On-farm Water Husbandry Research Reports Series No 3. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Sreedevi, T.K., Shiferaw, B. and Wani, S.P. (2004) Adarsha watershed in Kothapally: understanding the drivers of higher impact. *Global Theme on Agroecosystems Report No. 10*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Sreedevi, T.K., Wani, S.P., Sudi, R., Mahesh, S., Patel, J.T., Singh, S.N. and Shah, T. (2006) On-site and off-site impact of watershed development: a case study of Rajasamadhiyala, Gujarat, India. *Global Theme on Agroecosystems Report No. 20*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Sreedevi, T.K., Wani, S.P. and Pathak, P. (2007) Harnessing gender power and collective action through integrated watershed management for minimizing land degradation and sustainable development. *Journal of Financing Agriculture* 36, 23–32.

Stoorvogel, J.J. and Smaling, E.M.A. (1990) Assessment of soil nutrient depletion in sub-Saharan Africa: 1983–2000, 1: Main Report. Report No. 28. Winand Staring Centre, Wageningen, the Netherlands.

Thirtle, C., Beyers, L., Lin, L., Mckenzie-Hill, V., Irz, X., Wiggins, S. and Piesse, J. (2002) The impacts of changes in agricultural productivity on the incidence of poverty in developing countries. DFID Report No. 7946. Department for International Development (DFID), London, UK.

Twomlow, S., Shiferaw, B., Cooper, P. and Keatinge, J.D.H. (2006) *Integrating Genetics and Natural Resource Management for Technology Targeting and Greater Impact of Agricultural Research in the Semi-Arid Tropics*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

UNEP (United Nations Environment Programme) (1997) *World Atlas of Desertification*, Second Edition.

UN Millennium Project (2005) Investing in development: a practical plan to achieve the Millennium Development Goals, UN MDG, New York (www.unmillenniumproject.org) (accessed in May 2005).

UNSTAT (2005) www.unstat.com. Last accessed in 2005.

van Koppen, B., Namara, R. and Stafilios-Rothschild, C. (2005) Reducing poverty through investments in agricultural water management. Poverty and gender issues and synthesis of sub-Saharan Africa case study reports. Working Paper 101. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Wani, S.P., Pathak, P., Tam, H.M., Ramakrishna, A., Singh, P. and Sreedevi, T.K. (2002) Integrated watershed management for minimizing land degradation and sustaining productivity in Asia. In: Adeel, Z. (ed.) *Integrated Land Management in the Dry Areas*. Proceedings of a Joint UNU–CAS International Workshop, 8–13 September 2001, Beijing, China. United Nations University, Tokyo, Japan, pp. 207–230.

Wani, S.P., Pathak, P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003a) Improved management of vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19, 217–222.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003b) Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK; International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 199–215.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003c) Farmer-participatory integrated watershed management: Adarsha watershed, Kothapally, India. An innovative and up-scalable approach. A case study. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council, Consultative Group on International Agricultural Research, Washington, DC, pp. 123–147.

Wani, S.P., Balloli, S.S., Kesava Rao, A.V.R. and Sreedevi, T.K. (2004) Combating drought through integrated watershed management for sustainable dryland agriculture. In: *Regional Workshop on Agricultural Drought Monitoring and Assessment Using Space Technology*, 4 May 2004, National Remote Sensing Agency (NRSA), Hyderabad, India, pp. 39–48.

Wani, S.P., Singh, P., Dwivedi, R.S., Navalgund, R.R. and Ramakrishna, A. (2005) Biophysical indicators of agro-ecosystem services and methods for monitoring the impacts of NRM technologies at different scale. In: Shiferaw, B., Freeman, H.A. and Swinton, S.M. (eds) *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. CAB International, Wallingford, UK, pp. 97–123.

Wani, S.P., Reddy, M., Sreedevi, T.K. and Raju, D. (eds) (2006a) *Corporate Science and Technology Institutions – Partnerships for Inclusive and Sustainable Development and Economic Growth*: Proceedings of the CII-ICRISAT Workshop, 27 February 2006, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., Long, T.D., Wangkahart, T., Shiferaw, B., Pathak, P. and Kesava Rao, A.V.R. (2006b) Issues, concepts, approaches and practices in integrated watershed management: experience and lessons from Asia. In: *Integrated Management of Watersheds for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa; Lessons and Experiences from Semi-Arid South Asia.* Proceedings of the International Workshop held at ICRISAT, Nairobi, 6–7 December 2004. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India, pp. 17–36.

WHO (World Health Organization) (2000) Gender, health and poverty. Factsheet No. 25, (http://www.who.int/mediacenter/factsheets/fs251/en/).

World Bank (1982) *World Development Report 1982*. Oxford University Press, New York.

World Bank (2000) Spurring agricultural and rural development. In: *Can Africa Claim the 21st Century?* World Bank, Washington, DC, USA, pp. 170–207.

World Bank (2005) *Agricultural Growth for the Poor: an Agenda for Development.* The International Bank for Reconstruction and Development/The World Bank, Washington, DC.

2 Zooming in on the Global Hotspots of Rainfed Agriculture in Water-constrained Environments

J. Rockström* and L. Karlberg
Stockholm Environment Institute (SEI), Stockholm, Sweden;
*email: *johan.rockstrom@sei.se*

Introduction

Rainfed agriculture is practised on 80% of the world's agricultural area and generates 60–70% of the world's staple food[1] (FAOSTAT, 2005). In semi-arid and dry subhumid zones, rainfed agriculture dominates food production systems, and water is a key limiting factor to crop growth (SEI, 2005). Since approximately 70% of the world's poor are women, the importance of rainfed sources of food weighs disproportionately on women (WHO, 2000). Agriculture plays a key role for economic development (World Bank, 2005), poverty reduction (Irz and Roe, 2000) and economic growth (van Koppen *et al.*, 2005). Every 1% increase in agricultural yield translates to a 0.6–1.2% decrease in the percentage of absolute poor[2] (Thirtle *et al.*, 2002). In sub-Saharan Africa for example, agriculture accounts for 35% of the gross domestic product (GDP) and employs 70% of the population (World Bank, 2000), and more than 95% of the agricultural area is rainfed (FAOSTAT, 2005). Thus, in this region, agriculture is the engine of overall economic growth and, therefore, broad-based poverty reduction (Johnston and Mellor, 1961; World Bank, 1982; Timmer, 1988; Abdulai and Hazell, 1995; IFAD, 2001; DFID, 2002; Koning, 2002).

There are thus strong reasons to believe that in many areas poverty is strongly influenced by agricultural production, which in turn is dependent on climate in general and water availability in particular. Despite the complex driving forces behind poverty, the social–ecological interactions between livelihoods, agriculture and water constraints make it important to analyse the degree of interdependence and the regions of the world where these factors interact. Identifying such regions can provide an important guide for new investments in upgrading rainfed agriculture.

The aim of this chapter is to identify global hotspots of rainfed agriculture where water constitutes a key limiting factor to crop growth. Thus, the focus is on the dry subhumid, semi-arid and arid zones. First, we investigate the link between climate and poverty. Thereafter, the number of people living in water-constrained agricultural areas is estimated. Based on this analysis, the global hotspots for rainfed agricultural areas in water-constrained environments are identified.

Most Poor Live in Water-constrained Environments

There is a correlation between poverty and water stress (Falkenmark, 1986). The UN Millennium

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

Development Project has identified the hotspot countries in the world suffering from the largest prevalence of malnourishment. These countries coincide closely with those located in the semi-arid and dry subhumid hydroclimates of the world (Fig. 2.1), i.e. savannah and steppe ecosystems. Of the 850 million undernourished people in the world, essentially all live in poor developing countries, which predominantly are located in tropical and subtropical regions (UNSTAT, 2005).

A Fifth of the World's Population Lives in Water-constrained Agricultural Areas

To make a quantitative assessment of the number of people depending on rainfed and irrigated agriculture for their livelihoods in different hydroclimatic zones, geographically distributed data was analysed. An overview of the data sets is given in Table 2.1. All data sets were re-sampled to a resolution of 2.5 min and continuous variables were reclassified into discrete classes, except for population.

Data on land use were derived from the Global Land Cover data set (GLC2000, 2003), in which the class 'cultivated and managed areas'[3] was chosen to represent the total agricultural area. Second, a data set produced by the FAO (Food and Agriculture Organization, the United Nations) was used to represent irrigated agricultural land use (Siebert *et al.*, 2005). This data set shows the percentage of the agricultural area equipped for irrigation. We

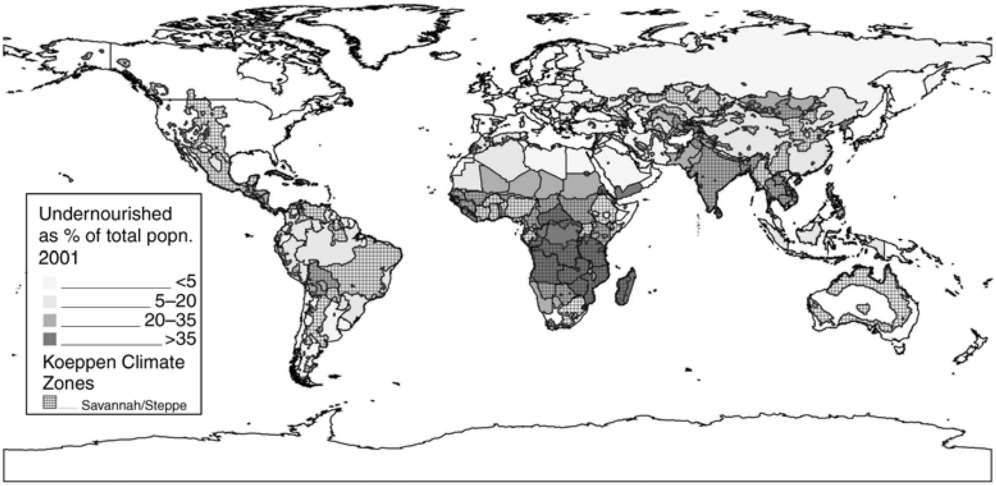


Fig. 2.1. The prevalence of undernourishment in developing countries (as percentage of population 2001/2002; UNSTAT, 2005), together with the distribution of semi-arid and dry subhumid hydroclimates in the world, i.e, savannah and steppe agroecosystems. These regions are dominated by sedentary farming subject to the world's highest rainfall variability and occurrence of dry spells and droughts.

Table 2.1. Datasets used in the analysis of hydroclimate, poverty and land use.

Dataset	Source (see text)	Resolution	Continuous data	Classes
Land use				
Agricultural land	GLC2000 FAO	0.5 min	NA[a]	Irrigated agriculture
Irrigated land	(Siebert *et al.*, 2005)	5 min		Rainfed agriculture/other
Hydroclimate	FAO based on CRU CL 2.0	5 min	Aridity index	Arid/semi-arid/dry subhumid/humid
Population	GPWv3	2.5 min	Number of people	NA[a]

[a] NA = data not available.

classified areas with more than 30% of the fields equipped for irrigation as 'irrigated agriculture', which corresponds to about 20% of the total agricultural area and is thus in accordance with the estimates by the FAO (FAOSTAT, 2003). Rainfed agricultural area was determined by subtracting irrigated agricultural area from the total agricultural area. This means that in pixels classified as irrigated, there might be rainfed fields as well, and vice versa. The classification is thus independent of rainfall amounts.

Water constraints are here defined only in terms of hydroclimate and described by an aridity index (AI)[4] provided by the FAO (2006). They created the AI data from climatic variables in the data set CRU CL 2.0 (New *et al.*, 2002), and by calculating reference potential evapotranspiration according to the Penman-Monteith equation as described by Allen *et al.* (1998). Because AI was given as a continuous variable in the data set, it had to be reclassified into four hydroclimatic zones: arid (AI < 0.20), semi-arid (AI 0.20 to <0.50), dry subhumid (AI 0.50 to <0.65) and humid (AI > 0.65). A global population data set, Gridded Population of the World (GPWv3), produced by SEDAC (Socio-Economic Data and Applications Centre), was used in the analysis (CIESIN and CIAT, 2005). A methodological documentation of the GPWv3 is given in Balk and Yetman (2004).

The analysis shows that approximately 50% of the total global land area is located in water-constrained regions (Table 2.2), which is slightly higher in comparison with other studies (e.g. Safriel and Adeel, 2005). In particular, the estimate of the arid zone area deviates from the literature value. About 36% of the global population live in areas subject to water constraints, a figure which is in agreement with other estimates (Safriel and Adeel, 2005). Thus, it seems that the differences in area estimation of the arid regions make little difference in terms of population, probably owing to low population density in arid regions.

Agricultural area is about 13% of the total land area, which corresponds well with data found in FAOSTAT (2003; data for arable land and permanent crops). Although this area is rather small, almost half of the global population (47%) lives in agricultural areas. This is slightly higher than the estimation by FAO from the year 2000 of 42% (FAOSTAT, 2000).

These data sets were then used to calculate the number of people living in agricultural areas in the different hydroclimatic zones. The results show that about 1.11 billion people, corresponding to 17% of the total global population, lives from agriculture in water-constrained environments (Fig. 2.2). Out of that, almost half (8.2% of the world population) lives in rainfed agricultural areas, while the other half (8.9% of the world population) lives in irrigated agricultural areas. In the arid zone, more people live in irrigated agricultural areas compared with rainfed agricultural areas, which is to be expected since irrigation is needed to secure crop yields. On the other hand, in slightly wetter areas (i.e. semi-arid and dry subhumid), more people live in rainfed agricultural areas compared with irrigated agricultural areas.

Table 2.2. Area of land population in different hydroclimatic zones and land use areas from GIS analysis.

Region	Area (% of total land area)	Population[a] (% of total)
Hydroclimate		
Arid (including hyperarid)	23 (17)[b]	7.2 (5.8)[b]
Semi-arid	18 (15)[b]	16 (14)[b]
Dry subhumid	9 (9)[b]	13 (15)[b]
Total	50 (41)[b]	36 (36)[b]
Land use		
Rainfed agriculture	11 (9.7)[c]	28
Irrigated agriculture	2.1 (2.1)[c]	19
Total	13 (12)[c]	47 (42)[d]

[a] Figures in parenthesis are literature values; [b] Safriel and Adeel (2005); [c]FAOSTAT (2003); [d] FAOSTAT (2000).

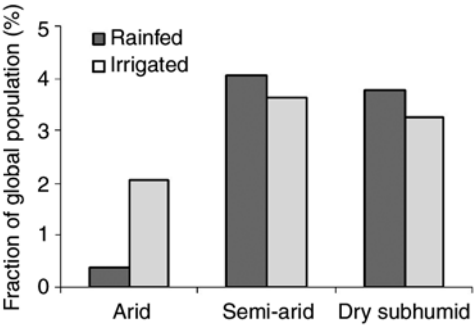


Fig. 2.2. Number of people in each hydroclimatic and land use zone in relation to the total global population.

Zooming in on the Hotspots for Water-constrained, Rainfed Agriculture

Three regions were identified as hotspots for water-constrained, rainfed agriculture, namely Africa, South Asia and East Asia (Fig. 2.3). Each of these regions hosts more than 100 million poor people depending on rainfed agriculture in water-constrained environments. Taken together, the total number of people in these three areas constitutes about 80% of all people living in water-constrained, rainfed agricultural areas, corresponding to 426 million people. In Africa, most of these people live in a band stretching from Senegal, through Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan, Ethiopia, Kenya, Tanzania, Zambia, Malawi, Mozambique, Zimbabwe and ending in South Africa. This area constitutes a large share of the total agricultural area in Africa, and in this region the prevalence of undernourishment is high (Fig. 2.1). The majority of the population living in water-constrained, rainfed agricultural areas in South Asia live in western India, and also partly in Pakistan and Afghanistan. Despite the fact that large parts of eastern India are agricultural land, this part of the country is substantially wetter, which explains the lack of people living in water-stressed conditions in that area. Lastly, in East Asia, the vast majority of the people living in water-constrained, rainfed agricultural areas are found on the north-eastern and north China plains. Although agricultural land extends further south in the country, it is only these two regions that are water constrained.

There is a clear difference between the three regions in terms of population density within the selected environment (Fig. 2.3); in Africa the population density is only about 0.5 persons per hectare, while it is more than four times greater in South Asia. Moreover, there is a difference between the three regions in terms of hydroclimate (Fig. 2.3). In comparison with the other regions, a relatively large part of the area is semi-arid in Africa, dry subhumid in East Asia, and arid in South Asia; however, in all three regions the semi-arid area dominates over the others, while the arid area is the smallest. Farming systems are similar in the three regions, with sedentary farming dominating in the semi-arid and dry subhumid regions, and with agropastoral systems in the transitional zone between dry semi-arid and semi-arid regions, particularly in Africa and East Asia. All three regions are dominated by small-scale rainfed farming, with a higher degree of mechanization in South and East Asia, as compared with Africa. Africa is the only region still practising (though limited) shifting cultivation.

Characteristic for Africa, South Asia and East Asia is that yields generally are lower than the world average[5], with a few exceptions (Fig. 2.4a). This can be viewed as an opportunity for improvements in the form of investments into water management in these regions, given the large opportunities for improved agricultural and water productivity even in water-constrained regions. Moreover, GDP is very low in both Africa and South Asia, in comparison with the world average, and also a little bit below the world average in East Asia (Fig. 2.4b). Poverty is thus generally prevalent in these regions, which hampers investments in agricultural inputs such as water management techniques and nutrients. The large number of people who depend on rainfed agriculture in water-constrained environments, the low yields and the high incidence of poverty in these regions can also be interpreted as a cause and effect relationship between water availability, crop production and poverty. In other words, where water limits crop production, poverty is strongly linked to variations in rainfall and to the farmers' ability to bridge intraseasonal dry spells. Livelihoods depend strongly on water availability, a relationship that is well established for economies highly dependent on the

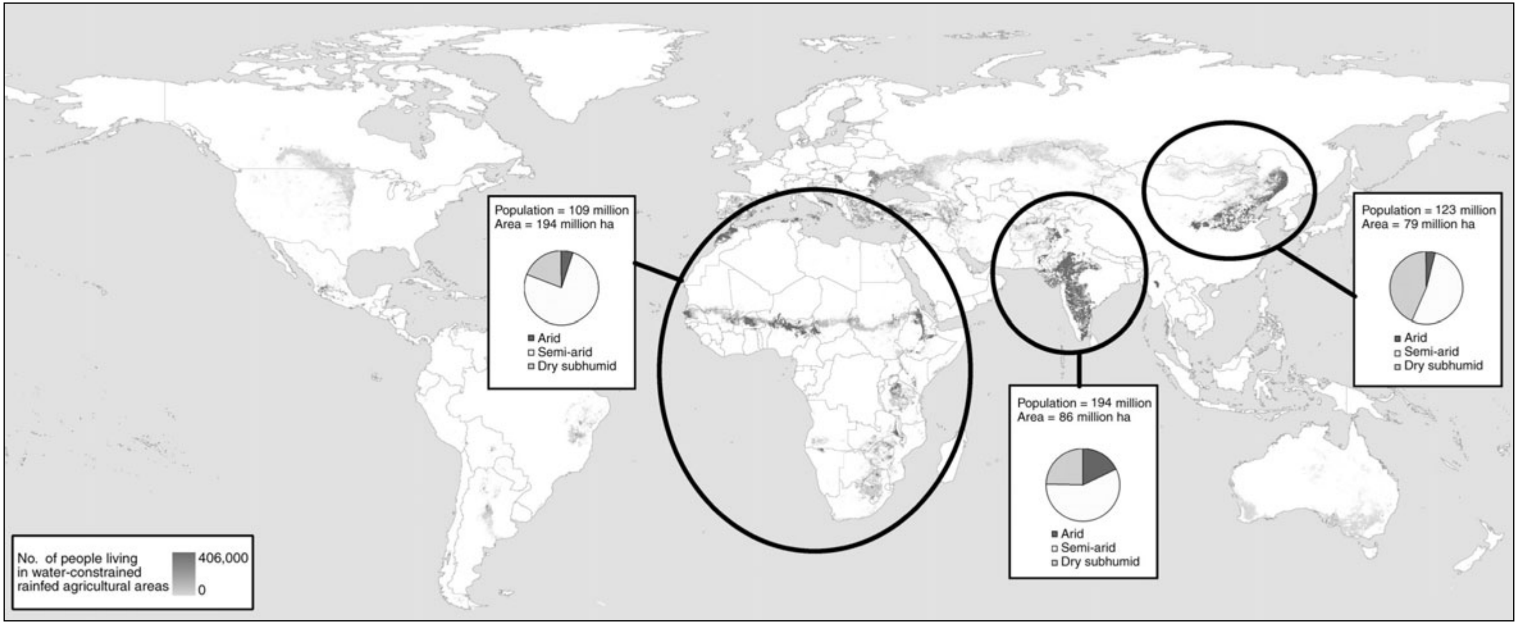


Fig. 2.3. Number of people living in water-constrained, rainfed agricultural areas. The three circles indicate the occurrence of global hotspots where more than 100 million people live.

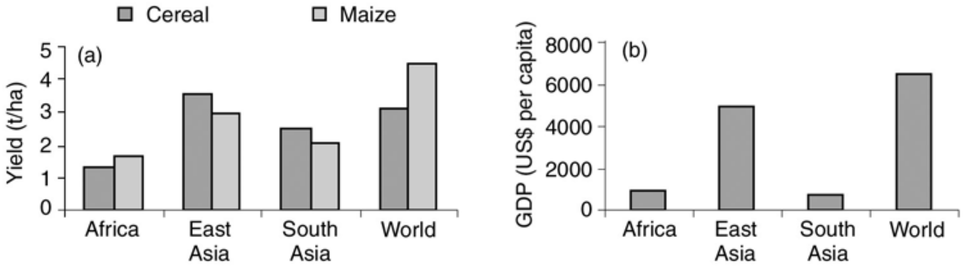


Fig. 2.4. Comparison between (a) average yields (FAOSTAT, 2003) and (b) gross domestic product (GDP) (UNSTAT, 2004) for the three global hotspot regions for water-constrained, rainfed agriculture. Cereals include barley, maize, millet, oats, rice, rye, sorghum and wheat. GDP for South Asia also includes data for Central Asia.

agrarian sector, resulting, for example, in a close correlation between average annual rainfall and GDP growth (Brown and Lall, 2006).

Linking Poverty, Land Use and Hydroclimate

Assessments of the relationships between poverty, hydroclimate and land use have previously not been conducted at a sub-national level, and therefore estimates on the number of poor that depend on rainfed agriculture as their main source of income, in areas where water poses constraints on agriculture, are still lacking. This chapter provides an identification of the global hotspots for combined water stress and rainfed agricultural land use. Moreover, the relationship between poverty and hydroclimate is discussed. The next step would be to quantitatively estimate the number of poor living off rainfed agriculture in water-constrained environments; however, such an analysis requires reliable global poverty data at a high resolution.

Conclusions

Poverty generally seems to be relatively prevalent in water-constrained areas. This could be due to the fact that many poor people's livelihoods depend on crop production from rainfed agriculture in water-constrained environments. It is estimated that about 1.11 billion people, corresponding to 17% of the total global population, live in agricultural areas in water-constrained environments, and out of that 8.2% of the population, lives specifically in rainfed agricultural areas. In Africa, East Asia and South Asia more than one million people in each region live in rainfed agricultural areas where water poses a key constraint for crop production. These regions are characterized by low crop yields and GDP levels. Again, this could be interpreted as an effect of water constraints on crop production, which in turn could affect poverty in regions where many people derive their livelihoods from rainfed agriculture. The conclusion would thus be that investments in water management to upgrade rainfed agriculture in these hotspot regions are likely to have a large impact on poverty reduction. Moreover, the Millennium Development Goals on hunger and poverty require increased focus on water management in rainfed agriculture.

Acknowledgements

We are very grateful to Duncan McConnachie, who provided invaluable help with the GIS-analysis. Jippe Hoogeveen, FAO, kindly shared the hydroclimate data set with us.

Notes

[1] Food that forms the basis of a traditional diet, and thus varies from place to place. Typically inexpensive starchy foods of vegetable origin, e.g. cereals that are high in calories and carbohydrate and that can be stored for use throughout the year.

[2] Poverty is generally understood as the condition of having little money and few material possessions. Factors that are part of poverty include: precarious livelihoods, excluded locations, physical limitations, gender relationships, social relationships, lack of security, abuse by those in power, limited capacities, disempowering institutions and weak community organizations. The term 'absolute poor' used in the chapter refers to poverty in relation to an absolute poverty threshold. In this chapter the term 'poor' refers to those 850 million people that are undernourished according to UNSTAT (2005).

[3] This class includes herbaceous, shrub and tree crops (irrigated and rainfed), as well as flooded crops.

[4] Precipitation divided by potential evapotranspiration.

[5] In the African hotspot, the main crops are maize, millet and sorghum, in South Asia it is millet and wheat and in the China hotspot it is wheat, maize and soybean.

References

Abdulai, A. and Hazell, P. (1995) The role of agriculture in sustainable development in Africa. *Journal of Sustainable Agriculture* 7(2/3), 101–119.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M. (1998) Crop evapotranspiration – guidelines for computing crop water requirements. FAO Irrigation and Drainage. Paper 56. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Balk, D. and Yetman, G. (2004) *The Global Distribution of Population: Evaluating the Gains in Resolution Refinement.* Center for International Earth Science Information Network (CIESIN), Columbia University, USA.

Brown, C. and Lall, U. (2006) Climate and development: the role of variability and a framework for resilience. *Natural Resources Forum* 30, 4.

CIESIN (Center for International Earth Science Information Network) and CIAT (Centro Internacional de Agricultura Tropical) (2005) *Gridded Population of the World Version 3 (GPWv3): Population Grids.* Socioeconomic Data and Applications Center (SEDAC), Columbia University, USA. (Available at http://sedac.ciesin.columbia.edu/gpw).

DFID (Department for International Development) (2002) Better livelihoods for poor people: the role of agriculture. Issues Paper. DFID Rural Livelihoods Department, London, UK (Consultation Document Draft A4).

Falkenmark, M. (1986) Fresh water – time for a modified approach. *Ambio* 15(4), 192–200.

FAO (2006) Aridity-index global data set. 5 min resolution. Provided by Jippe Hoogeveen. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAOSTAT (2000) http://faostat.fao.org/ (last accessed November 2005).

FAOSTAT (2003) http://faostat.fao.org/ (last accessed November 2005).

FAOSTAT (2005) http://faostat.fao.org/ (last accessed November 2005).

GLC2000 (The Global Land Cover Map for the Year 2000) (2003) GLC2000 database. European Commission Joint Research Centre (http://www-gem.jrc.it/glc2000).

IFAD (2001) *Rural Poverty Report 2001: the Challenge of Ending Rural Poverty.* International Fund for Agricultural Development (IFAD), Oxford, UK.

Irz, X. and Roe, T. (2000) Can the world feed itself? Some insights from growth theory. *Agrekon* 39(3), 513–528.

Johnston, D.G. and Mellor, J.W. (1961) The role of agriculture in economic development. *American Economic Review* 51(4), 566–593.

Koning, N. (2002) Should Africa protect its farmers to revitalise its economy? Working Paper North–South Centre. Wageningen University and Research Centre, Wageningen, the Netherlands.

New, M., Lister, D., Hulme, M. and Makin, I. (2002) A high-resolution data set of surface climate over global land areas. *Climate Research* 21, 1–25.

Safriel, U. and Adeel, Z. (2005) Dryland systems. In: Hassan, R., Scholes, R. and Ash, N. (eds) *Ecosystems and Human Well-being, Current State and Trends,* Vol. 1. Millennium Ecosystem Assessment, Island Press, Washington, USA, pp. 623–662.

SEI (2005) Sustainable pathways to attain the Millennium Development Goals – assessing the role of water, energy and sanitation. Document prepared for the UN World Summit, 14 September 2005, New York, USA. Stockholm Environment Institute, Stockholm, Sweden (http:// www.sei.se/mdg.htm).

Siebert, S., Döll, P., Feick, S. and Hoogeveen, J. (2005) Global Map of Irrigated Areas Version 3.0. Johann Wolfgang Goethe University, Frankfurt am Main, Germany; and Food and Agriculture Organization of the United Nations, Rome, Italy (http://www.fao.org/geonetwork/srv/en/main.home; last accessed November 2006).

Thirtle, C., Beyers, L., Lin, L., Mckenzie-Hill, V., Irz, X., Wiggins, S. and Piesse, J. (2002) The impacts of changes in agricultural productivity on the incidence of poverty in developing countries. DFID Report No. 7946. Department for International Development (DFID), London, UK.

Timmer, C.P. (1988) The agricultural transformation. In: Chenery, H. and Srinivasan, T.N. (eds) *Handbook of Development Economics*, Vol. 1. North-Holland, Amsterdam, the Netherlands, pp. 113–135.

UNSTAT (2004) www.unstat.com (last accessed in 2004).

UNSTAT (2005) www.unstat.com (last accessed in 2005).

van Koppen, B., Namara, R. and Stafilios-Rothschild, C. (2005) Reducing poverty through investments in agricultural water management. Poverty and gender issues and synthesis of sub-Saharan Africa case study reports. Working Paper 101. International Water Management Institute (IWMI), Colombo, Sri Lanka.

WHO (2000) Gender, health and poverty. Factsheet No. 25. June (http://www.who.int/mediacenter/factsheets/fs251/en/).

World Bank (1982) *World Development Report 1982*. Oxford University Press, New York, USA.

World Bank (2000) Spurring agricultural and rural development. In: *Can Africa Claim the 21st Century?* The World Bank, Washington, DC, USA, pp. 170–207.

World Bank (2005) *Agricultural Growth for the Poor: an Agenda for Development*. The International Bank for Reconstruction and Development/The World Bank, Washington, DC, pp.1–19.

3 Water Resource Implications of Upgrading Rainfed Agriculture – Focus on Green and Blue Water Trade-offs

L. Karlberg,[1]* J. Rockström[1] and M. Falkenmark[2]
[1]*Stockholm Environment Institute (SEI), Stockholm, Sweden;*
[2]*Stockholm International Water Institute (SIWI), Drottninggatan 33,*
SE-111 51 Stockholm, Sweden;
*email: *louise.karlberg@sei.se*

Introduction

Every increase in water use in agriculture will affect water availability for other water-dependent uses, both direct human use (water supply) and ecosystem use (terrestrial and aquatic ecosystems). In overcommitted watersheds, upgrading rainfed agriculture through investments in water-harvesting systems may result in severe water trade-offs with downstream users and ecosystems (Calder, 1999). Even so, the downstream impacts on stream flow from small-scale water storage systems have been shown to be very limited in some cases, even as a result of large-scale implementation (Evenari *et al*., 1971; Schreider *et al*., 2002; Sreedevi *et al*., 2006). Investing in water management in rainfed agriculture can lead to positive environmental impacts on other ecosystems, as a result of reduced land degradation and relative improvement of water availability (i.e. enabling more food to be produced with *relatively* less water) and water quality downstream.

Rainfall is partitioned in two categories of freshwater resource: a *green water* resource, i.e. the soil moisture generated from infiltrated rainfall that is available for root water uptake by plants, and which constitutes the main water resource in rainfed agriculture; and a *blue water* resource, i.e. the stored run-off in dams, lakes and aquifers, which is the main water source for irrigated agriculture (Fig. 3.1) (Falkenmark, 1995). These green and blue water resources generate flows in the hydrological cycle. Green water flows are the vapour flows that go back to the atmosphere (evaporation, interception and transpiration) and amount to 65% of global precipitation (Rockström *et al*., 1999; Rockström

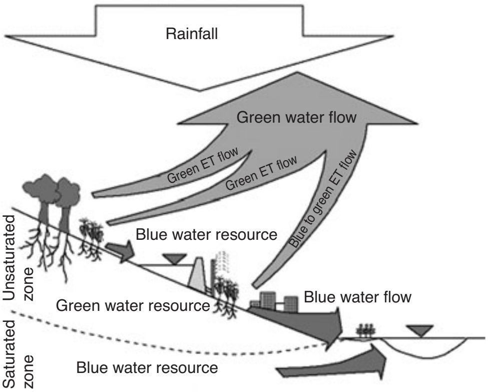


Fig. 3.1. Green and blue water resources and flows in rainfed and irrigated agriculture (ET = evapotranspiration).

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al*.)

and Gordon, 2001; Falkenmark and Rockström, 2004). Blue water flows, on the other hand, are the liquid flows of water recharging groundwater and flowing in rivers to lakes, wetlands and ultimately the ocean, and amount to 35% of global precipitation. It has been estimated that the total green water flow from croplands globally is around 6800 km^3/year (Rockström *et al.*, 1999), which corresponds to around 6% of global precipitation. Of this, 5000 km^3/year originates from rainfed agriculture, and the remainder from irrigated agriculture (Rockström *et al.*, 1999).

In a holistic view on water, as depicted in Fig. 3.1, water is regarded as the bloodstream of the biosphere. The water continuum starts off as rainwater and flows through the terrestrial ecosystems as surface water, groundwater and soil water, until it leaves the surface as a consumptive flow (green water flow) or discharges into the sea. During its journey through the landscape it can be used and reused as long as it is not consumed. It is collected for drinking purposes, stored in water-harvesting devices and used for supplementary irrigation in rainfed agriculture, dammed to produce hydropower, and withdrawn for irrigation purposes. Irrigation drain water can be used again to irrigate more salt-tolerant crops further downstream. Water fills up lakes used for tourism, fisheries and navigation. It is used by households and industries, after which it is purified and again re-enters the ecosystems. The most beneficial use of water depends on the local conditions, the quantity and quality of the water and the location within the basin. In developed countries, a larger share of the water resource is allocated towards industry compared with developing countries. Thus, in the future we can expect the demand of water from industry to gradually increase in those countries classified as developing countries today.

In closed and closing basins, more water is used than is renewably available in a river basin during at least part of the year. This situation puts constraints on water management within the basin, as described by Molden *et al.* (2001) and Molle (2003). However, improvements in water productivity, land-use change and decreased evaporative losses of blue water from rainwater captured close to the source convey larger opportunities to upgrade rainfed agriculture than hitherto believed. This chapter aims to give an overview of the implications of upgrading rainfed agriculture on green and blue water resources and flows. Special attention is given to trade-offs between upstream implementation of water management techniques for rainfed agriculture and the impacts on the downstream water users and ecosystems. The potential for minimizing trade-offs is discussed, and finally some implications on policy making are addressed.

Options for Upgrading Rainfed Agriculture

Improved crop yields and water productivity can be accomplished in many ways (Critchley and Siegert, 1991), as summarized in Table 3.1. One option is to maximize plant water availability in the root zone, which involves practices to capture surface run-off for *ex-situ* water harvesting and supplemental irrigation, redirect local run-off to the plant roots and maximize rainfall infiltration through *in-situ* water management, and by managing soil evaporation. Second, management can be targeted at maximizing the plant water-uptake capacity, which involves practices of crop and soil management to increase root water uptake. To achieve these aims, there is a wide spectrum of integrated land and water management options. Some of them focus on increasing water productivity, such as mulch practices, drip irrigation techniques, and crop management to enhance canopy cover, while most of them primarily aim at improving crop production by capturing more water.

Implications on Green and Blue Water Resources

The fundamental principle behind green and blue water resources in agriculture is that plants take up water from the root zone in the uppermost part of the soil profile, i.e. the green water resource, which subsequently leaves the plant as transpiration, i.e. a *productive* green water flow (as opposed to *non-productive* green flows as evaporation and interception). In rainfed agriculture the green water resource mainly originates from naturally infiltrated rainwater,

Table 3.1. Rainwater management strategies and corresponding management options to improve crop yields and water productivity.

Rainwater management strategy	Purpose	Management options
Increase plant water availability *Ex-situ* (external) water-harvesting systems	Dry spell mitigation, protective irrigation, spring protection, groundwater recharge, enable off-season irrigation, multiple water use	Surface micro-dams, subsurface tanks, farm ponds, percolation dams/tanks, diversion and recharging structures
In-situ water-harvesting systems	Concentrate run-off to cropped area and/or other use	Bunds, ridges, broad-beds and furrows, micro-basins, run-off strips
	Maximize rainfall infiltration	Terracing, contour cultivation, conservation agriculture, dead furrows, staggered trenches
Evaporation management	Reduce non-productive evaporation	Dry planting (early), mulching, conservation agriculture, intercropping, windbreaks, agroforestry, early plant vigour, vegetative bunds, optimum crop geometry
Increase plant water uptake capacity Integrated soil and crop management	Increase proportion of water balance flowing as productive transpiration	Improved crop varieties, soil fertility, optimum crop rotation, pest control, organic matter

but it can be augmented through irrigation by allowing the application of blue water resource to infiltrate the land. At this stage it is perhaps pertinent to point out that irrigated versus rainfed agriculture is a distinction made in the realm of agronomy and water resource management, which does not have any basis in hydrology. The difference in hydrological terms between irrigated and rainfed agriculture, as defined in this Comprehensive Assessment, is that in rainfed agriculture the main part of the green water resource originates from naturally infiltrated rainfall, whereas in irrigated agriculture yields depend to a large extent on external inputs of blue water to augment the green water resource (i.e. blue to green water redirections). In reality, irrigated agriculture depends to a significant degree on infiltrated rainfall as a supplementary water resource, and many of the key strategies to improve rainfed agriculture involve supplementary addition of blue water resources.

Table 3.2 outlines the major water management strategies and the implications of those on blue and green water resources. By improving water productivity through water management that aims at minimizing non-productive green water losses, more green water will be available for crop production. This results in higher yields for the same amount of green water use. Irrigation expansion, on the other hand, means that blue water is captured and is allowed to infiltrate in the field, thereby augmenting the green water resource in a process that can be described as blue to green water redirection. The green water resource is also augmented when strategies to improve the local use of rainfall are implemented through *in-situ* rainwater harvesting. This takes place at the partitioning point when rainwater either infiltrates the soil to form green water or generates run-off to form blue water. In effect, the process results in an increase in the green water resource and a corresponding decrease in the blue water resource. Yields can also be improved by converting non-agricultural land to agriculture. Green water that previously sustained the former ecosystem is then used for crop production instead. The impact on the blue water resource depends on differences in water demand and infiltration capacity between the two systems. Non-conventional water sources like saline water and drainage water from industries can also be used sustainably in agriculture if combined with proper management (Karlberg, 2005). In this case, precipitation is supplemented by an additional water source, resulting in an augmentation of both blue and green water.

Table 3.2. Implications of water management strategies on blue and green water resources.

Water management strategy	Implications on blue and green water resources
Improving water productivity (demand management) e.g. evaporation management, integrated soil, crop and water management, deficit irrigation	Reduce green water losses
Expanding irrigation (supply augmentation) e.g. *ex-situ* rainwater harvesting and supplemental irrigation	Adding blue water to the field, blue to green redirection
Improving local use of rainfall (supply augmentation) e.g. *in-situ* rainwater harvesting such as conservation agriculture	Reduce blue water losses, increase green water resources
Agricultural area expansion (supply augmentation)	Convert green water use in natural ecosystems to green water use in agriculture. Possible effects on blue water generation
Use of non-conventional water sources (supply augmentation) e.g. desalinization of seawater, use of marginal-quality water, reuse of drainage water from cities and industries	Adding more water to the hydrological cycle, generating more blue and green water

Sometimes, water management strategies target only demand management. For example, when mulch is applied to the field the non-productive green water flow is reduced, and thus more green water is available for productive green water flow. The net result is a higher yield for the same amount of green water used, i.e. an improved water productivity. However, improved water productivity is often also a secondary result of enhanced crop growth due to either improved supply or demand management. Larger plants have canopies that shadow a larger area of the soil surface. This shadowing effect is important since it leads to lower soil evaporation, which in turn results in more green water for productive green water flow and concurrent improvements in water productivity. Thus, there are important feedback links between supply and demand management.

Impacts of Water Management Strategies on Downstream Water Users and Ecosystems

From the previous section it is clear that many of the strategies to upgrade rainfed agriculture will impact on both the hydrological flows within the watershed and also directly on the non-agricultural terrestrial ecosystem through agricultural area expansion. Many of these impacts will require trade-offs between water for food production and water for other purposes.

Water productivity improvements entail a vapour shift between non-productive and productive green water use (Fig. 3.2a). Such a shift does not affect the blue water resource and as such does not have any specific negative or positive implications for downstream ecosystems or water users.

By expanding irrigation through *ex-situ* water harvesting, less blue water is available downstream (Fig. 3.2b). Therefore, less water is left to sustain downstream terrestrial and aquatic ecosystems and to satisfy downstream industrial, domestic and agricultural water use. Irrigation expansion is thus likely to result in trade-offs with other ecosystems and water users. The magnitude of this trade-off depends on the amount of water captured upstream and the volumes of water lost to evaporation during the conveyance from upstream to downstream, as well as the need for water downstream.

When *in-situ* soil water harvesting is implemented, less blue water is generated from precipitation due to higher infiltration of rainwater (Fig. 3.2c). Thus, the effect on downstream water users and ecosystems is similar to that originating from expanding irrigation, i.e. trade-offs can be expected. However, it is mainly the surface run-off component of the total blue water flow that is lower, while subsurface run-off is likely to be affected to a lesser degree.

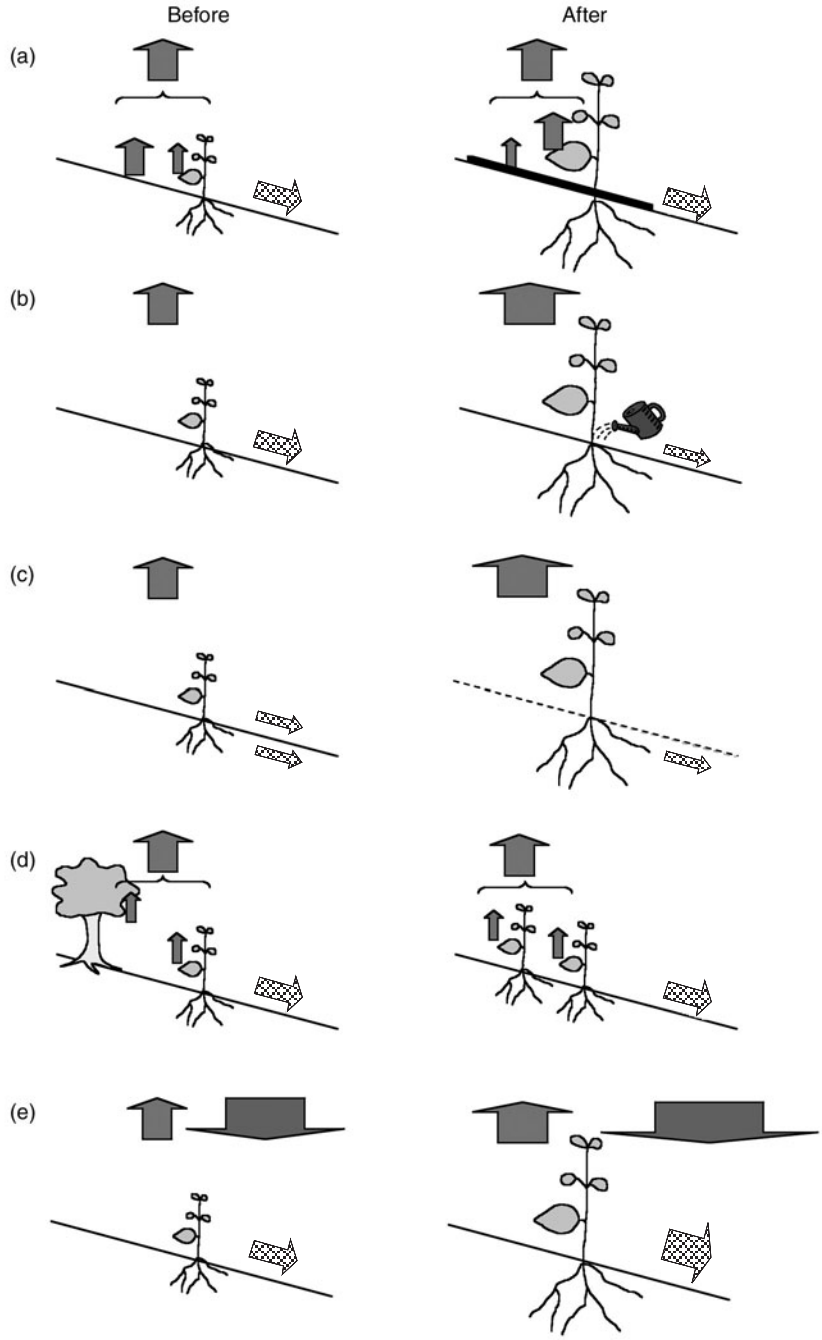


Fig. 3.2. Impacts on green (shaded arrows) and blue (hatched arrows) water flows of different water management strategies before (left) and after (right) implementation, (a) improving water productivity, (b) *ex-situ* water harvesting, (c) *in-situ* water harvesting, (d) agricultural area expansion, (e) use of non-conventional water sources.

Expanding the agricultural area has a direct effect on adjacent ecosystems as it inevitably encroaches on other ecosystems. Trade-offs with other land uses, such as forestry, biofuel production and pasture, are therefore to be expected, as well as impacts on biodiversity. Agricultural area expansion probably also affects blue water flows (Fig. 3.2d); however, whether this means a reduction or an increase will depend on the change in soil infiltrability and vegetation type.

Many of the non-conventional water resources that have been suggested for agricultural water use are of marginal quality, and if not managed properly can cause salinization, build-up of heavy metals and health concerns from pathogens. Although the use of non-conventional water resources might not necessarily have any negative impacts on other ecosystems or water users in terms of water amounts (Fig. 3.2e), water quality factors might, in fact, be very problematic.

Opportunities for Minimizing Trade-offs

There are several opportunities to minimize the trade-offs between water consumption for food and water consumption for other purposes. Even if it might not be possible to completely eliminate all trade-offs, they could be decreased substantially.

In rainfed agriculture, yields are currently very low in many regions (see Chapter 6, this volume). Yield improvements in low-productivity regions result in relatively large improvements in water productivity, compared with high-productivity regions (Fig. 3.3). Therefore, investments in *in-situ* or *ex-situ* water harvesting in rainfed agriculture that are able to increase yields from 1 t/ha to 2 t/ha would result in a concurrent improvement of water productivity from approximately 3500 m^3/t to less than 2000 m^3/t. The same gains in water productivity would not be possible at higher productivity levels common to large-scale irrigated agriculture.

Another benefit of investments in *ex-situ* water harvesting is that the collected water can be used for an off-season, fully irrigated cash crop. If this period coincides with the winter season, radiation and air temperature are likely to be low, and thus the atmospheric demand for water. The consequence of this is higher water productivity.

When blue water is formed and travels through the landscape to the sea, some of this water is being evaporated along the way. Moreover, a large part of the blue water is generated during storms and is lost from the basin in

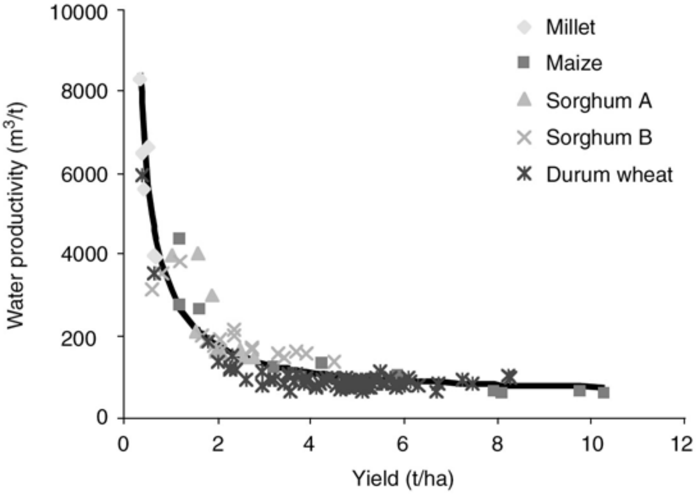


Fig. 3.3. Dynamic relationship between green water productivity and yield for cereal crops in different climatic conditions and management. Data from: Rockström *et al.* (1998) (millet), Stewart (1988) (maize), Dancette (1983) (sorghum A), Pandey *et al.* (2000) (sorghum B) and Zhang and Oweis (1999) (durum wheat). Regression line after Rockström (2003).

large pulses of water without any beneficiary use, also causing problems with erosion (Bewket and Sterk, 2005). Improvements in the local use of rainwater (*in-situ* water harvesting) mean that water is being used close to the source of rainfall, i.e. within the farmer's field. In this way, evaporation losses from the blue water resources become smaller, less water is lost as storm run-off and erosion problems are restricted. Thus, in general, upstream capture of blue water for agriculture is more advantageous compared with downstream. Since rainfed agriculture is often located upstream, investments in upgrading water management in rainfed agriculture might convey less trade-offs with other water users and ecosystems, compared with investments in irrigated agriculture, which is often located downstream. Moreover, *in-situ* water harvesting primarily reduces surface run-off, while subsurface run-off is reduced to a lesser degree. The latter blue water resource should be preferred, since it causes less erosion and evaporation losses are smaller. Therefore, *in-situ* water harvesting has an advantage compared with other irrigation management techniques.

The hydrological impact of agricultural area expansion at the watershed scale depends on land use prior to conversion into agriculture. Historic land-cover change has reduced the green water flows to the atmosphere, owing to conversions from natural ecosystems to agriculture (Gerten *et al.*, 2005). Similarly, a modelling exercise over land use in a semi-arid catchment in South Africa indicated a reduction in blue water flows from increased forestry (Jewitt *et al.*, 2004). Therefore, by replacing forest plantations with agricultural land, a positive effect on downstream blue water availability can be expected. Expanding agriculture into degraded lands with low infiltration capacity is likely to result in more groundwater formation (blue water) as well as reduced floods and erosion during heavy storms.

Assessments of Implications of Water Management Strategies for Upgrading Rainfed Agriculture Require a Holistic Approach

From the above analysis of impacts of different water management strategies in rainfed agriculture, it is clear that the interactions between different management strategies are complex and that the impacts depend on many factors, such as the location of the agricultural fields in relation to other ecosystems and water users in the watershed, climatic factors and present agricultural productivity. This calls for a holistic approach to evaluate trade-offs between all water users and ecosystems from different water-impacting water management strategies (Falkenmark, 2000). The starting point for such an approach has to be the rainfall over the river basin. However, with globalization, the issue of spatial scales becomes increasingly important as food and other water-consuming goods are produced and consumed in different river basins. In addition, with changing climate, addressing the implications of various temporal scales is highly relevant. The latter is also of importance for comparisons between annual and perennial crops. Fortunately, tools that handle temporal changes at different spatial scales are available today and could be applied in catchments to form a platform for informed decision making on water management, although at present this is very rarely done.

It is well established that *in-situ* and *ex-situ* water-harvesting techniques are useful for improving yields in small-scale rainfed agriculture where water is the key limiting production factor to growth; however, the question that remains to be answered is what effect large-scale adoption of these techniques would have on green and blue water resources in the watershed. For example, what would the return to investments in upgrading rainfed agriculture be in terms of water productivity, yields and money, compared with similar investments in large-scale irrigation? There is a need for more research that targets these issues at the watershed level, which can translate into decision-support tools for water planners and policy makers.

Looking beyond the realm of rainfed agriculture, it is clear that most ecosystems today are in one way or another affected by human activity, and that the choice of land use inevitably affects the hydrological cycle (Falkenmark, 2000). Forests, for instance, consume on average 720 mm/year (green water flow) compared with 510 mm/year for grasslands (Rockström and Gordon, 2001). These figures give an indication of the implications a change in land use might have on the hydrological flows in the catchment.

Examples of deforestation and reforestation from Australia, South Africa and Hungary illustrate how conversions of land use result in downstream blue water depletion as well as waterlogging and salinization.

Especially in catchments where the key limiting factor to biomass growth is water, an integrated analysis of the impact of different land use options on poverty alleviation, livelihoods, economic return of water (i.e. amount of money gained per drop of water consumed) and ecosystem resilience is needed to make informed decisions on optimum land management strategies. To argue that the water management strategy that causes 'minimum disturbance of natural ecosystems' should always be implemented ignores the fact that humans are not separate from the ecosystems but in fact form an integral part of them. In order to satisfy societal needs, humans have to manipulate various landscape elements. Therefore, the challenge is to find the 'best possible manipulation' of the ecosystems and not the 'least possible manipulation' (Falkenmark, 2003).

Policy Implications

The agricultural sector is heavily reliant not only on the green water resource but also on blue water to varying degrees. In order to achieve efficient water management on the national level, the legislation governing water resources management must account for both green and blue water use, especially in regions where water poses a constraint on economic development and the trade-offs between water users and ecosystems are substantial. This is gradually being realized throughout the world. In South Africa, the National Water Act from 1998 stipulates that a reserve of water, incorporating water for basic human needs and environmental flows, is given the highest priority in terms of water allocations. Moreover, the importance of green water flows is partly acknowledged in the legislation. The law regulates the trade-off between upstream activities such as forestry that have an impact on stream flow through increased use of green water and downstream water users.

Changes in land and water use upstream impact on water availability downstream. With increasing demand for water, particularly in basins and catchments subject to water scarcity, there is an increasing realization of the need to develop policy options that address water trade-offs between upstream and downstream water demands. An innovative, incentive-based policy initiative has been taken by IFAD (the International Fund for Agricultural Development), where a 'Green Water Credit' (GWC) system is piloted in the Tana river basin in Kenya. The objective is to create an incentive-based system for improved green water management in upper catchments (i.e. reduce non-productive vapour flows in land management upstream in order to increase blue water availability downstream). Water credits are given to upstream land and water users by downstream water-using sectors (e.g. industry and irrigated agriculture) as payment for increased blue water availability. Such a mechanism requires the ability to carry out catchment assessments of current water use and partitioning and estimates of increased release of water when adopting different water-saving technologies (e.g. conservation tillage, water-harvesting practices, mulching and drip irrigation).

At the regional level, there is a need for efficient tools to assess green and blue water flows to be able to compare different water management strategies and to study the impact of changing the land use in an area. Such decision-support tools must be user-friendly and flexible to suit the local conditions. Moreover, they must be able to operate in areas where data availability is limited.

There are economic pay-offs for downstream societies of investments upstream in improved water and land management. Examples are emerging in different parts of the world where downstream communities compensate upstream communities for economic gains of environmental services downstream received because of wise water management investments upstream (FAO, 2004). However, most documented experiences have so far largely been of deforestation and/or afforestation in the upstream watershed (Perrot-Maître and Davis, 2001; Landell-Mills and Porras, 2002).

Training of extension officers in the realm of water management working at the local level is crucial for adoption of new techniques to upgrade rainfed agriculture. Through the extension officers, the farmers get access to new knowledge and strategies for improving current yield levels.

Conclusions

In most cases, water management strategies to upgrade rainfed agriculture will result in trade-offs with downstream water users and ecosystems. However, depending on the choice of management strategy, these trade-offs can be minimized. An increase in yield in areas where the productivity is presently very low results in a relatively large improvement in water productivity, compared with yield improvements in areas with higher yields. Improvements in water productivity causes a vapour shift, which means that the productive flows of green water increase while the non-productive flows decrease to the same extent, and hence blue water flows are not affected at all. Therefore, investments in rainfed agriculture, such as *in-situ* or *ex-situ* water harvesting, where yields are low at present might cause comparatively large improvements in water productivity. Moreover, the augmentation of the green water resource in *in-situ* water harvesting comes from blue water that has been captured close to the source. This leads to lower evaporative losses of blue water compared with when the blue water is used for irrigation further downstream and also limits erosion. An integrated approach is needed to assess the impact of different investment strategies in rainfed agriculture in terms of poverty alleviation, livelihoods, economical returns and ecosystem resilience. The conclusion is that there seems to be ample room for improving yields in rainfed agriculture, while at the same time limiting trade-offs with downstream water users and ecosystems.

References

Bewket, W. and Sterk, G. (2005) Dynamics in land cover and its effects on stream flow in the Chemoga watershed, Blue Nile, Ethiopia. *Hydrological Processes* 19, 445–458.

Calder, I.R. (1999) *Blue Revolution: Land Use and Integrated Water Resources Management*. Earthscan, London, UK.

Critchley, W. and Siegert, K. (1991) *Water Harvesting: a Manual for the Design and Construction of Water Harvesting Schemes for Plant Production*. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Dancette, C. (1983) Estimation des besoins en eau des principales cultures pluviales en zone Soudano-Sahélienne. *L'Agronomie Tropicale* 38(4), 281–294.

Evenari, M., Shanan, L. and Tadmor, N.H. (1971) *The Negev: the Challenge of a Desert*. Harvard University Press, Cambridge, Massachusetts, USA.

Falkenmark, M. (1995) Land–water linkages: a synopsis. In: *Land and Water Integration and River Basin Management*. FAO Land and Water Bulletin No. 1. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 15–16.

Falkenmark, M. (2000) Competing freshwater and ecological services in the river basin perspective – an expanded conceptual framework. *Water International* 25(2), 172–177.

Falkenmark, M. (2003) Freshwater as shared between society and ecosystems: from divided approaches to integrated challenges. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences* 358, 2037–2049.

Falkenmark, M. and Rockström, J. (2004) *Balancing Water for Humans and Nature: the New Approach in Ecohydrology*. Earthscan, London, UK.

FAO (2004) Payment schemes for environmental services in watersheds. Regional Forum, 9–12 June 2003 in Arequipa, Peru. Land and Water Discussion Paper No. 3. FAO, Rome, Italy.

Gerten, D., Hoff, H., Bondeau, A., Lucht, W., Smith, P. and Zaehle, S. (2005) Contemporary 'green' water flows: simulations with a dynamic global vegetation and water balance model. *Physics and Chemistry of the Earth* 30, 334–338.

Jewitt, G.P.W., Garrat, J.A., Calder, I.R. and Fuller, L. (2004) Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth* 29, 1233–1241.

Karlberg, L. (2005) Irrigation with saline water using low-cost drip-irrigation systems in sub-Saharan Africa. PhD thesis, KTH Architecture and the Built Environment, Stockholm, Sweden.

Landell-Mills, N. and Porras, T.I. (2002) *Silver Bullet or Fools' Gold? A Global Review of Markets for Forest Environmental Services and their Impact on the Poor*. Instruments for Sustainable Private Sector Forestry Series, International Institute for Environment and Development, London, UK (http://www.iied.org/pubs/pdf/full/9066IIED.pdf).

Molden, D.J., Sakthivadivel, R. and Keller, J. (2001) *Hydronomic Zones for Developing Basin Water Conservation Strategies*. Research Report 56, International Water Management Institute (IWMI), Colombo, Sri Lanka.

Molle, F. (2003) *Development Trajectories of River Basins – a Conceptual Framework*. Research Report 72. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Pandey, R.K., Maranville, J.W. and Admou, A. (2000) Deficit irrigation and nitrogen effects on maize in a Sahelian environment: I. Grain yield and yield components. *Agricultural Water Management* 46(1), 1–13.

Perrot-Maître, D. and Davis, P. (2001) *Case Studies of Markets for Innovative Financial Mechanisms for Water Services from Forests*. Forest Trends, Washington, DC, USA (http://www.forest-trends.org).

Rockström, J. (2003) Water for food and nature in the tropics: vapour shift in rainfed agriculture. *Philosophical Transactions of the Royal Society of London Series B – Biological Sciences* 358(1440), 1997–2009.

Rockström, J. and Gordon, L. (2001) Assessment of green water flows to sustain major biomes of the world: implications for future ecohydrological landscape management. *Physics and Chemistry of the Earth* 26(11–12), 843–851.

Rockström, J., Jansson, P.-E. and Barron, J. (1998) Estimates of on-farm rainfall partitioning in pearl millet field with run-on and run-off flow based on field measurements and modelling. *Journal of Hydrology* 210, 68–92.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapour flows, food production and terrestrial ecosystem services. *Conservation Ecology* 3(2), 5, 1–28 (http://www.consecol.org/vol3/iss2/art5).

Schreider, S.Y., Jakeman, A.J., Letcher, R.A., Nathan, R.J., Neal, B.P. and Beavis, S.G. (2002) Detecting changes in streamflow response to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia. *Journal of Hydrology* 262(1–4), 84–98.

Sreedevi, T.K., Wani, S.P., Sudi, R., Mahesh, S., Patel, J.T., Singh, S.N. and Tushar, S. (2006) *On-site and Off-site Impact of Watershed Development: a Case Study of Rajasamadhiyala, Gujarat, India*. Global Theme on Agroecosystems, Report No. 20. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, 502 324, Andhra Pradesh, India.

Stewart, J.I. (1988) *Response Farming in Rainfed Agriculture*. The WHARF Foundation Press, Davis, California, USA.

Zhang, H. and Oweis, T. (1999) Water–yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. *Agricultural Water Management* 38, 195–211.

4 Tectonics–Climate-linked Natural Soil Degradation and its Impact in Rainfed Agriculture: Indian Experience

D.K. Pal,* T. Bhattacharyya, P. Chandran and S.K. Ray**
*Division of Soil Resource Studies, National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Amravati Road, Nagpur 440 010, India; emails: *dkpal@nbsslup.ernet.in; **tapas11156@yahoo.com*

Introduction

Soil is the most basic of all resources and the primary substrate for growing crops. It is also non-renewable over the human timescale. This basic fact made all scientists, agriculturists, environmentalists and policy makers anxious about whether soil resources will remain capable to feed, clothe and shelter the expected 8.2 billion inhabitants of the world by the year 2030 (www.unpopulation.org). The available land resources are gradually diminishing because, on a global scale, land resources and population are unevenly distributed. Soils, being most dynamic, are able to supply nutrients, buffer acid and base reactions, destroy and absorb pathogens, detoxify and attenuate xenobiotic and inorganic compounds and have the capacity for self-restoration through soil formation. However, soil formation is a slow process, and a substantial amount of soil can form only over a geologic timescale. Soil misuses and extremes of condition can upset these self-regulating attributes and cause a soil to regress from a higher to a lower type of usefulness and/or drastically diminish its productivity (Lal *et al.*, 1989). This unfavourable endowment of soils has been termed 'soil degradation'.

Definition, Processes and Factors of Soil Degradation

Definition

Lal *et al.* (1989) defined soil degradation as 'Diminution of soil quality (and thereby its current and potential productivity) and/or a reduction in its ability to be a multi-purpose resource due to both natural and man-induced causes.' However, such an explanation remains undefined since it is not related to a quantitative value of crop yield beyond which soils can be considered as degraded. Sodicity tolerance ratings of crops in loamy-textured soils of the Indo-Gangetic Plains (IGP) indicated that a 50% reduction in relative yield was observed when exchangeable sodium percentage (ESP) in soils was above 50 for rice and around 40 for wheat (Abrol and Fireman, 1977). In shrink–swell soils (vertisols), an optimum yield of cotton can be obtained when soils are non-sodic (ESP <5) and have saturated hydraulic conductivity (sHC) ≥ 20 mm/h. About 50% reduction in yield occurs when soils are sodic (ESP >5) and exhibit sHC <10 mm/h. However, the Ca-zeolitic sodic haplusterts of Rajasthan and Gujarat states of India do support rainfed crops fairly well (Pal *et al.*, 2006a) because of their favourable sHC

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

(>10 mm/h). Therefore, fixing a lower limit of sodicity (Pal *et al.*, 2006a) at ESP >40 for soils of the IGP (Abrol and Fireman, 1977), at ESP >5 but <15 for Indian vertisols (Kadu *et al.*, 2003), at ESP 6 for Australian soils or at ESP >15 for all soil types (Soil Survey Staff, 1999) appears to be irrelevant to the performance of crops in highly sodic vertisols with soil modifiers, especially Ca-zeolites (Pal *et al.*, 2006a). In view of the pedogenetic processes that ultimately impair the hydraulic properties of soils of dry climates mediated through dispersibility, the most important factor of soil degradation, Pal *et al.* (2006a) advocated a value of sHC <10 mm/h (as weighted mean in 0–100 cm depth of soil) to define sodic soils instead of any ESP.

Processes

Processes that lead to soil degradation include accelerated erosion, increasing wetness and poor drainage, laterization, salinization, nutrient imbalance, decline in soil organic matter, and reduction in activity and species activity of soil fauna and flora (Lal *et al.*, 1989). Processes of soil degradation have been identified as chemical, physical and biological actions and interactions that would affect the capacity of a soil for self-regulation and its productivity.

Factors

Factors causing soil degradation are both natural and man-induced agents and catalysts that induce the processes leading to changes in properties of soils and the attributes for their life support (Lal *et al.*, 1989). Although some pedogenic processes, such as laterization, hardsetting, fragipan formation and clay-pan formation, are hitherto considered as natural soil degradation processes as they lead to less-desirable physical and chemical conditions, causing degradation of soils (Hall *et al.*, 1982; Lal *et al.*, 1989), the majority of the information on soil degradation, whether at national (Sehgal and Abrol, 1992, 1994), regional (FAO, 1994) or international level (Oldeman, 1988; UNEP, 1992), centres around only human-induced degradation. However, a few recent studies in the Indian subcontinent at the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India showed that the development of sodicity is also a natural process of soil degradation in arid and semi-arid climatic conditions (Balpande *et al.*, 1996; Pal *et al.*, 2000, 2001, 2003a,b,c, 2006a; Vaidya and Pal, 2002).

Climate, Neotectonic and Soil Degradation

In response to the global climatic event during the Quaternary, the soils of many places of the world witnessed climatic fluctuations, especially in the last post-glacial period. Frequent climatic changes occurred during the Quaternary (Ritter, 1996). Tectonic slopes/faults determine the courses of large rivers (Singh *et al.*, 2006) and play a significant role in the evolution of geomorphology and soils (Srivastava *et al.*, 1994; Kumar *et al.*, 1996; Singh *et al.*, 1998; Pal *et al.*, 2003c, 2006b). Crustal movements also caused the change in climate from humid to semi-arid, as experienced with the formation of the Western Ghats (Brunner, 1970). In the FAO's (1994) endeavour to record land degradation in South Asia, the potential effects of global climatic change to cause degradation in soils were not considered. It was, however, envisaged that if adverse changes occur in some areas, then these will certainly constitute a most serious form of human-induced degradation of natural resources. It is quite likely, however, that the current aridic environment prevailing in many parts of the world, including India (Eswaran and van den Berg, 1992), may create adverse physical and chemical environments that may reduce the productivity of soils. Thus a new research initiative to follow the changes in soil properties by identifying the 'pedogenic threshold' due to tectonic-induced climate change can help us in expanding our basic knowledge in pedology and also in creating a relevant database. Such a database, although not sufficient, could be of high importance in any attempt to adapt sustainable soil management and long-range resource management strategies for many developing nations belonging to the arid and semi-arid parts of the world.

Maintenance of the agricultural productivity in arid and semi-arid lands of the world would ever remain a great challenge, including in the Indian subcontinent, where arid and semi-arid environments cover more than 50% of the total geographical area (Pal *et al.*, 2000). There is no dearth of literature on soil degradation due to anthropogenic activities (Oldeman, 1988; Sehgal and Abrol, 1992, 1994; UNEP, 1992; FAO, 1994). This chapter, however, presents a few case studies to indicate the severe consequences of the natural degradation triggered by tectonic and climatic events. Such information will expand the present knowledge on soil degradation, which is necessary to protect the livelihood of humankind.

Natural Soil Degradation in Major Soil Types of India

Degradation in ferruginous soils

Ferruginous soils are tropical soils. They occur in the geographic tropics, i.e. in that region of the earth lying between the Tropic of Cancer and the Tropic of Capricorn. The tropics comprise approximately 40% of the land surface of the earth. Thus more than one-third of the soils of the world are tropical soils (Eswaran *et al.*, 1992). Ferruginous soils are the group of soils variously termed as 'red', 'brown', 'yellow', 'laterite', 'lateritic', 'ferralitic' and 'latosols', because they lack precise definition (Rengasamy *et al.*, 1978), and in India, these soils occupy about 70 million ha, covering about 21% of the total geographical area (Sehgal, 1998).

The present-day climate is too dry to have caused the iron accumulation in ferruginous soils of peninsular India. The laterization process must have taken place during the earlier humid tropical climate. Brunner (1970) reported evidence for tectonic movements during the Pliocene–Pleistocene transition which caused the formation of different relief types and relief generation. With the formation of the Western Ghats during the Plio-Pleistocene crustral movements, the humid climate of the Miocene–Pliocene was replaced by the semi-arid conditions which continue to prevail to date in the area. The Arabian Sea currently confronts the Western Ghats, which rise precipitously across to an average height of 1200 m. The result is an orographic rainfall, being heavy all along the west coast. The lee-side towards the east receives less than 1000 mm rainfall and is typically rain-shadowed (Rajaguru and Korisettar, 1987). Occurrence of numerous ferruginous soils capping the detached plateau at an average elevation of about 1100 m above mean sea level with an annual rainfall of more than 5000 mm (Anonymous, 1984) along the Western Ghats suggests that an extensive peneplained surface with a general southerly slope and moderate relief existed earlier in this area (Sahasrabudhe and Deshmukh, 1981). In some parts of southern India, laterite mounds and laterite plateau remnants are scattered over the landscape (Rengasamy *et al.*, 1978; Subramanian and Mani, 1981). In central India, thin to thick (0.25–3 m) laterite cappings cover various rock types, ranging in the age from Archean to Gondwanas (Pascoe, 1965; Sahasrabudhe and Deshmukh, 1981; Subramanian and Mani, 1981). Extensive, massive granitic tors in gneissic terrain bear the evidence of exhumation (Pal *et al.*, 1989) during an arid period following prolonged deep weathering in the humid tropical climate that prevailed from the Upper Cretaceous (Subramanian and Mani, 1981) until the Plio-Pleistocene. The Plio-Pleistocene was a transition period when the climate became drier with the rising of the Western Ghats (Brunner, 1970). As a result, the upper layers of the ferruginous soils (alfisols) formed in the preceding tropical humid climate were truncated by multiple arid erosional cycles (Rengasamy *et al.*, 1978; Chandran *et al.*, 2000; Srivastava *et al.*, 2001). Due to truncation of the upper layers of the alfisols, the clay contents presently show an upward increase from the C to the B horizons (Fig. 4.1a). The clay fractions are dominated by both kaolin and smectite (Pal *et al.*, 1989; Chandran *et al.*, 2000; Srivastava *et al.*, 2001) and bear the evidence of transformation of smectite to kaolin (Pal *et al.*, 1989). The present-day warm semi-arid climatic conditions are not considered severe enough for transformation of smectite to kaolin, and the neutral to alkaline reaction of these soils does not favour the transformation of 2:1 layer minerals to kaolin but favours the formation of pedogenic $CaCO_3$ (PC) (Fig. 4.1b). The adverse aridic climatic conditions induce the precipitation of $CaCO_3$, thereby depriving the soils of Ca^{2+} ions in exchange complex, with a con-

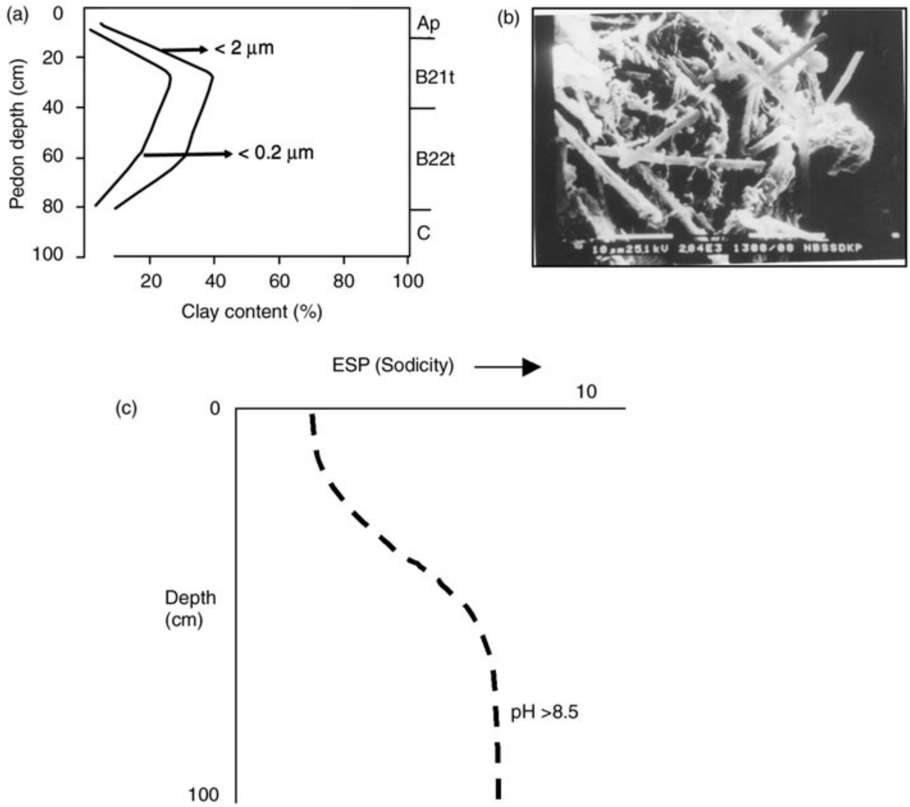


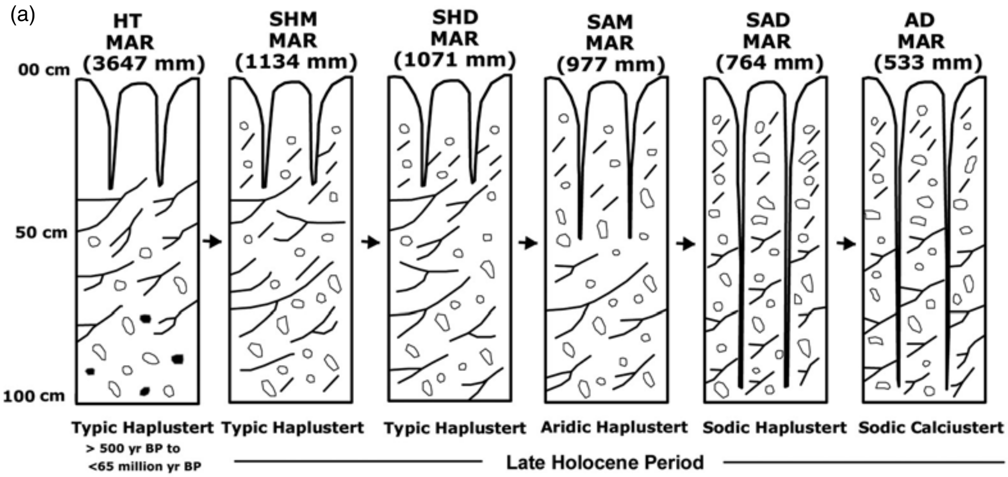
Fig. 4.1. (a) Clay distribution with pedon depth of representative ferruginous soils; (b) lubinites (pedogenic $CaCO_3$ (PC)) as evidence of supersaturation with $CaCO_3$ in arid climate in ferruginous soils; (c) concomitant development of sodicity with the formation of PC in subsoils of ferruginous soils (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

comitant chemical degradation in terms of development of sodicity in the subsoils (Fig. 4.1c). The rate of formation of $CaCO_3$ was estimated to be 0.2 mg/100g soil/year in 0–100 cm profile depth (Pal *et al.*, 2000).

Degradation in vertisols

The global distribution (except in Antarctica) of vertisols and vertic intergrades indicates that an area of 257 million ha are confined between 45° N and 45° S latitudes, of which India occupies nearly 30% area (Dudal, 1965). Vertisols occur in wider climatic zones of the world (Ahmad, 1996) and in India they belong to humid tropical (HT), subhumid moist (SHM), subhumid dry (SHD), semi-arid moist (SAM), semi-arid dry (SAD) and arid dry (AD) climatic environments (Fig. 4.2a) in the states of Madhya Pradesh, Maharashtra, Chhattisgarh, Karnataka, Andhra Pradesh, Tamil Nadu, Gujarat, Rajasthan and West Bengal (Kalbande *et al.*, 1992; Srivastava *et al.*, 2002; Kadu *et al.*, 2003; Pal *et al.*, 2003a, 2006a; Bhattacharyya *et al.*, 2005, 2006a,b, 2007a; Ray *et al.*, 2006). However, the occurrence of vertisols (Fig. 4.2a) in HT (Bhattacharyya *et al.*, 2005), SHM, SHD, SAM, SAD and AD climatic environments (Pal *et al.*, 2003a) in Deccan basalt area apparently suggests that the basaltic material has influenced soil formation in such a way that similar soils are formed under different climatic conditions (Mohr *et al.*, 1972).

A dominance of smectitic clay minerals causes appreciable shrink–swell phenomena, which



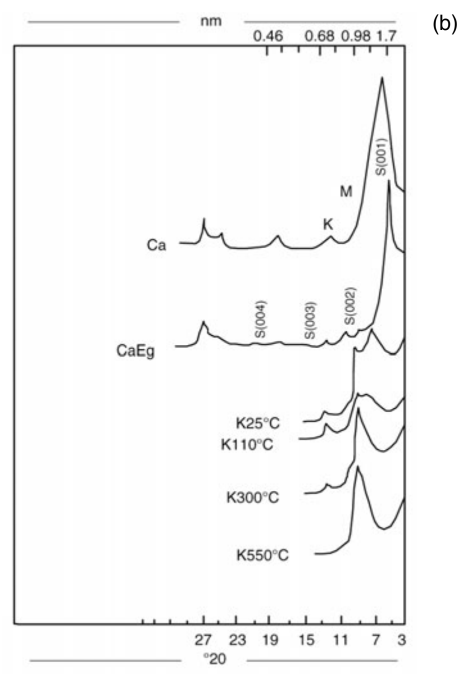


Fig. 4.2. (a) Successive stages of pedogenic evolution of vertisols in a climosequence (with decreasing mean annual rainfall); HT = humid tropical, SHM = subhumid moist; SHD = subhumid dry; SAM = semi-arid moist; SAD = semi-arid dry; AD = arid dry; (b) representative X-ray diffraction patterns of fine clay smectite of vertisols from subhumid, semi-arid and arid climates of peninsular India: S = smectite, M = mica, K = kaolin, Ca = Ca-saturated; Ca-EG = Ca-saturated and glycolated; K 25/110/300/550 °C = K-saturated and heated at 25, 110, 300 or 550 °C (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

induce the formation of cracks and distinctive structural elements in the form of sphenoids and wedge-shaped peds with smooth or slicken-sided surfaces (Eswaran *et al.*, 1988). Smectites are ephemeral in HT climate and they transform to kaolin (Pal *et al.*, 1989; Bhattacharyya *et al.*, 1993). Thus it is difficult to reconcile the formation of vertisols in HT climate. However, the presence of smectites and Ca-zeolites made the formation of vertisols possible in a lower physiographic situation, even under HT climate (Bhattacharyya *et al.*, 1993, 1998). It is equally difficult to understand the formation of vertisols in SHM, SHD, SAM, SAD and AD climates, since a large amount of smectite clay is required for their formation. In these climatic environments, the weathering of primary minerals contributes very little towards the formation of smectites, and the formation of PC is the primary chemical reaction responsible for the increase in pH, exchangeable magnesium percentage and ESP (Pal *et al.*, 2003b, 2006a). Thus the formation of such vertisols reflects a positive entropy change (Srivastava *et al.*, 2002). X-ray diffraction analysis of fine clays indicates that smectites are fairly well crystallized, as evident from a regular series of higher-order reflections, though short and broad, and do not show any sign of transformation (Fig. 4.2b) except for hydroxy-interlayering (Srivastava *et al.*, 2002; Pal *et al.*, 2003a).

These soils have both non-pedogenic $CaCO_3$ (NPC) and PC (Fig. 4.3). The NPCs have sharp boundaries with the soil matrix and are coated with Fe–Mn oxides (Fig. 4.3a). Brewer (1976) stated that such forms are pedorelic features. Based on ^{14}C dates of carbonate nodules, Mermut and Dasog (1986) concluded that vertisols with Fe–Mn-coated $CaCO_3$ glaebules are older than those with white $CaCO_3$ glaebules, i.e. PC. The PCs are formed in soils of dry climates (Pal *et al.*, 2000). This suggests that NPCs were formed in a climate much wetter than the present, which ensured adequate soil water for reduction and oxidation of iron and manganese to form Fe–Mn coats. Thus the smectites must have formed in an earlier humid climate, its crystallinity being preserved in the non-leaching environment of the latter subhumid to dry climates (Fig. 4.2b).

The ^{14}C age of soil organic carbon (OC) of these vertisols was estimated to be between 3390 and 10,187 years BP (Pal *et al.*, 2003a, 2006a). This suggests that the change from humid to drier climate occurred in peninsular India during the late Holocene (Pal *et al.*, 2001, 2003a, 2006a; Deotare, 2006). Vertisols of HT climate are dominated by Ca^{2+} ions in their exchange complex throughout the depth (Bhattacharyya *et al.*, 2005). However, in lower horizons of vertisols of subhumid to arid climates, the Mg^{2+} ions lead to dominate in the exchange complex (Pal *et al.*, 2003a). The soils

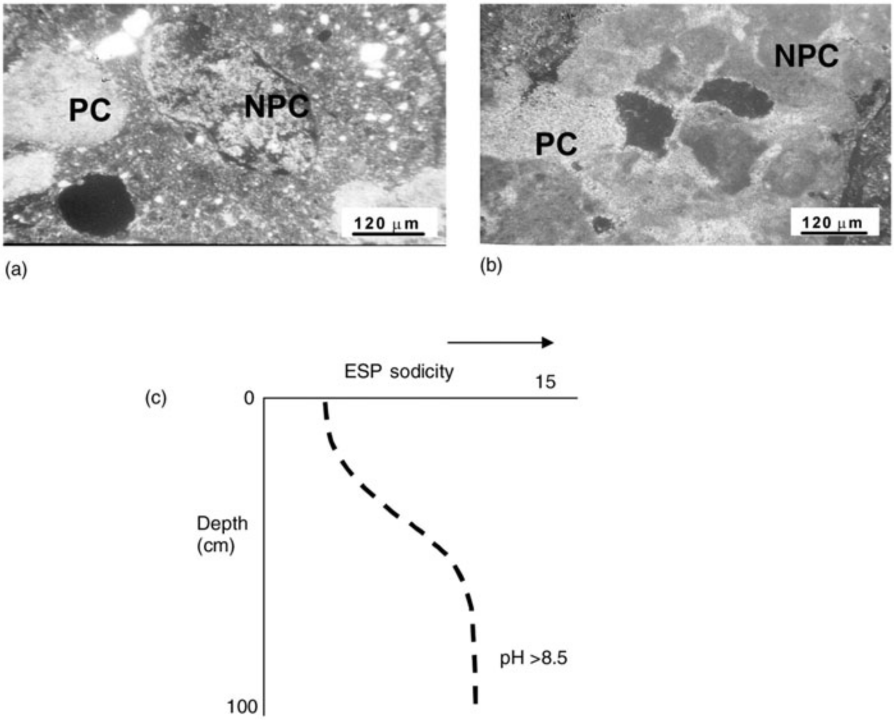


Fig. 4.3. (a) Pedogenic (PC) and non-pedogenic (NPC) $CaCO_3$ in vertisols; (b) the formation of PC at the expense of NPC; (c) concomitant development of sodicity with the formation of PC in subsoils of vertisols (Source: Division of Soil Resource Studies, NBSS&LUP, Nagpur, India).

of SAM, SAD and AD climates become more calcareous and sodic (ESP 5–15 with sHC <10 mm/h) (Pal *et al.*, 2006a) than those of SHM and SAM climates. The observations confirm the polygenesis in vertisols (Pal *et al.*, 2001) as the climate becomes drier during the Holocene. The formation of PC at the expense of NPC (Fig. 4.3b) is the prime chemical reaction responsible for increase in pH, the decrease in the Ca/Mg ratio of the exchange sites with depth and in the development of subsoil sodicity (Fig. 4.3c). It is the basic and natural process of soil degradation for the development of calcareous sodic soils (Pal *et al.*, 2000). The rate of formation of PC was estimated to be 0.25 mg/100g soil/year in the 0–100 cm of the profile depth (Pal *et al.*, 2000).

Earlier studies (Balpande *et al.*, 1996) on the factors and processes of soil degradation in vertisols of the Purna Valley of central India indicated that the semi-arid climate characterized by a mean annual rainfall (MAR) of 875 mm and a tropustic moisture regime causes the development of calcareous sodic soils. However, recent observations (Vaidya and Pal, 2002) indicated that in the adjacent east upland (Pedhi watershed) of the Purna Valley, vertisols have subsoil sodicity despite the fact that the area receives a higher MAR (975 mm) than the Purna Valley. Vertisols of the watershed occur on both micro-high (MH) and micro-low (ML) positions and the distance between MH and ML positions is approximately 6 km and the elevation difference is 0.5–5 m. The soils of the MH positions are strongly alkaline and those of the ML positions are mildly alkaline (Fig. 4.4a). Formation of sodic vertisols in MH positions alongside non-sodic vertisols in ML positions is a unique phenomenon. It develops because of microtopographic differences which modify distribution of water across the landscape and facilitate greater penetration of rainwater in ML positions. The degradation of soils in terms of the development of sodicity due to microtopographic differences in vertisols in the higher MAR zone of an overall semi-arid climate possibly indicates the subtle role of neotectonics in creating the MH and ML positions in the Purna Valley, which is an outcome of complex interplay/interaction of tectonic, climatic and other geological parameters (Ghatak *et al.*, 2005).

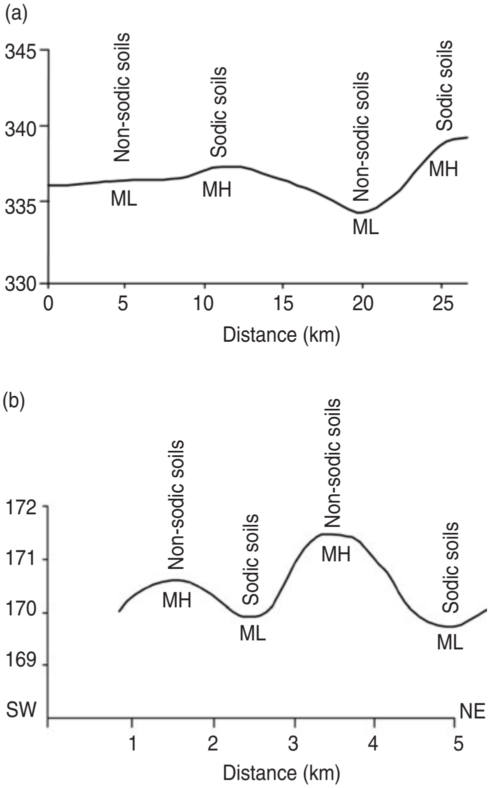


Fig. 4.4. Juxtaposition of the occurrence of sodic and non-sodic soils on micro-high (MH) and micro-low (ML) positions in (a) black soil region (BSR) and (b) the Indo-Gangetic Plains (IGP). Y-axis = elevation (msl).

Degradation in soils of the Indo-Gangetic Plains (IGP)

The IGP came into existence through collision of the Indian and Chinese plates. The Indian plate is still moving at the rate of 2–5 cm/year towards the north, and forming the world's highest mountain range on its border. The north–south compression generated through the plate ensures that it is continually under stress and provides the basic source of accumulating strain in the fractured zones (Gaur, 1994). The fluvial deposits and landforms of the IGP have been influenced by the stresses directed towards the north and north-east (Parkash *et al.*, 2000). The major rivers of the Plain have changed their courses and, at present, are flowing in south-east and easterly directions with convexity towards the south-west, which is strikingly similar to the arcuate pattern of the major thrusts bordering the Plains (Parkash *et al.*, 2000). Thus, the IGP show a series of terraces, bars and meandering scars resulting in MH and ML areas in the apparently smooth topography (Mohindra *et al.*, 1992; Srivastava *et al.*, 1994; Kumar *et al.*, 1996; Singh *et al.*, 2006). Many observations in Punjab (Sehgal *et al.*, 1975), Haryana (Bhumbla *et al.*, 1973) and Uttar Pradesh (Agarwal and Mehrotra, 1953; Srivastava *et al.*, 1994; Kumar *et al.*, 1996) indicate that the sodic soils occupy these ML areas, 50–100 cm lower than the MH areas, which have less sodic soils (Fig. 4.4b). The post-glacial warm period, in which human civilization developed and flourished, represents a short epoch, which began 10,000 years BP. Within the present interglacial period too, thermal conditions have continued to change. It is believed that monsoons were much stronger in the early part of the interglacial period. Around 4500–3700 years BP, the rainfall in the Indus Valley was probably much more than double the amount received now, and thus both agriculture and forestry flourished (Randhawa, 1945; Prasad and Gadgil, 1986). The paleoclimatic record has been documented from the north-west and south-west parts of India (Singh *et al.*, 1972, 1974, 1990). Climatic variations have also been inferred from Holocene soils (Srivastava *et al.*, 1994, 1998; Singh *et al.*, 2006). During pedogenesis two major regional climatic cycles are recorded: relatively arid climates between 10,000 and 6500 years BP and 3800 years BP and a warm and humid climate punctuated between these aridic climates (Srivastava *et al.*, 1998; Pal *et al.*, 2006b).

Sodic soils interspersed with non-sodic or less sodic soils occur in both canal-irrigated and unirrigated areas of the semi-arid parts of the IGP. Therefore, the introduction of canal irrigation in the IGP is not the reason for development of the sodic soils. Pal *et al.* (2003c) demonstrated that the main soil-forming processes were clay illuviation, deposition of PC and concomitant development of subsoil sodicity in these soils. The ML areas are repeatedly flooded with surface water during brief high-intensity showers, so the soils are subject to cycles of wetting and drying. This provides a steady supply of alkalis by hydrolysis of feldspar, leading to precipitation of $CaCO_3$ at high pH and development of subsoil sodicity. This impairs the hydraulic conductivity of soils and eventually leads to the development of natrustalfs, with ESP increasing up the profile (Fig. 4.5). The semi-arid climate and topography interact to facilitate greater penetration of bicarbonate-rich water in ML than MH positions. Thin sections show deformational pedofeatures such as cross- and reticulate-striation of plasmic fabric, disruption of clay pedofeatures, carbonate nodules and elongation of voids as a result of tectonic activity during the Holocene (Pal *et al.*, 2003c, 2006b). There is also support from geodetic observations that an area under tectonic compression undergoes horizontal movements and slow changes of height. By creating ML and MH sites, the tectonic activity may also have been ultimately responsible for degrading soils in terms of the formation of more and less sodic soils (Fig. 4.4b) (Pal *et al.*, 2003c). The rate of formation of $CaCO_3$ in these soils was estimated to be 0.86 mg/100 g soil/year in the 0–100 cm profile (Pal *et al.*, 2000).

Pedogenic Threshold in Dry Climates and Loss in Soil Productivity

Pedogenic thresholds

Case studies presented here indicate that the soils are becoming calcareous and sodic. Formation of PC facilitates the illuviation of clay

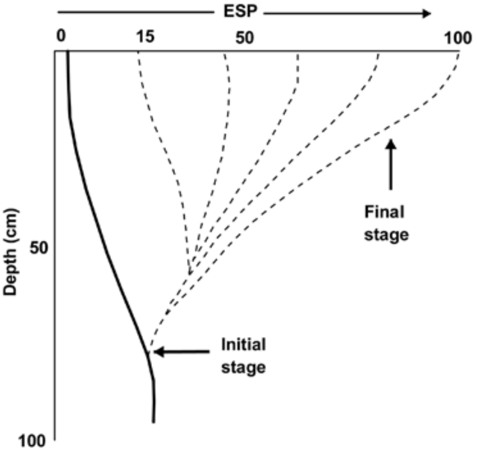


Fig. 4.5. Progressive development of sodicity in soils of the Indo-Gangetic Plains in a semi-arid environment.

particles and these two are concurrent, contemporary and active pedogenic processes. Thus it provides examples of pedogenic threshold in soils of semi-arid climate during the Holocene (Pal *et al.*, 2003b), which signifies the natural degradation process induced by neotectonic and climatic events (Fig. 4.6). An example from benchmark vertisols with and without soil modifiers (Ca-zeolites and gypsum) representing a climosequence from SHM to AD climate (Table 4.1) indicates that dry climate during the late Holocene restricted further leaching and as a result formation of PC was favoured (Pal *et al.*, 2001). The amount of PC in soils of a representative climatic region in the first 1 m of the profile (Table 4.1) indicates a general progressive increase in the rate of formation of PC (from 0.39 to 2.12 mg/100 g soil/year) and ESP (from 1 to 28) from subhumid to arid climate (Table 4.1).

Loss in soil productivity

Inefficient cropping and water application in irrigation commands result in a rise in groundwater and soil salinity and sodicity problems. Over the years, these problems have been so severe that misgivings are being raised on the sustainability of irrigated agriculture in canal irrigation commands (Abrol and Chaudhary, 1988).

Loss due to irrigation

There are instances to indicate that productive black soils under rainfed conditions have been degraded to such an extent that they are now not usable for agriculture. Such a problem is not only confined to an irrigation command area but also occurs in areas where river or well waters are used for irrigation (Nimkar *et al.*, 1992; Pal *et al.*, 2003a). This dismal scenario in non-zeolitic and

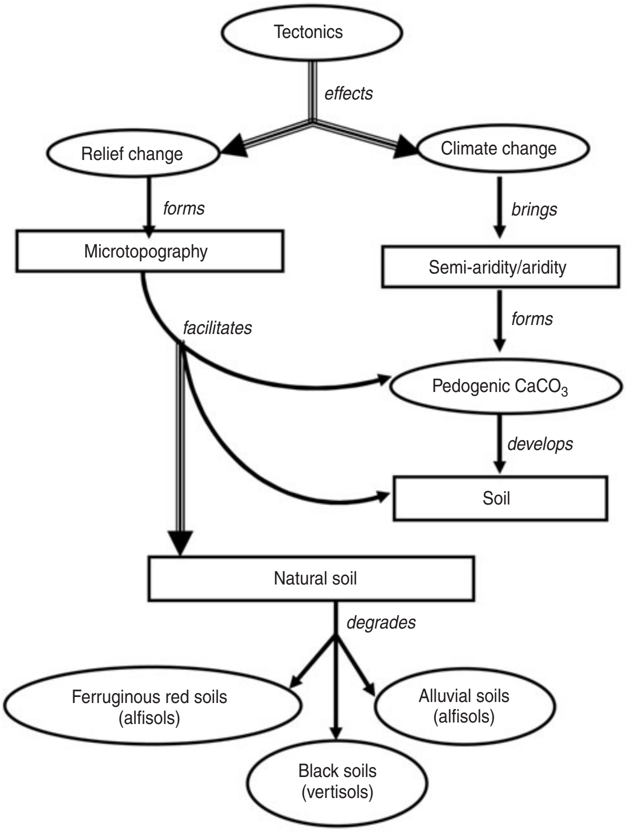


Fig. 4.6. Tectonics-induced natural soil degradation model.

Table 4.1. Rate of formation of PC and concomitant development of ESP in vertisols of a representative climatic region in India[a].

Soil series (soil taxonomy) (district, state)	$CaCO_3$ (%) weighted mean in the first 1 m of the profile	Rate of formation of PC in the first 1 m of the profile mg/100 g soil/year	Maximum ESP in the first 1 m of the profile	sHC (mm/h) weighted mean in the first 1 m of the profile
Subhumid moist (MAR 1209 mm) Nabibagh (typic haplusterts) (Bhopal, Madhya Pradesh)	3.7	0.39	~ 1	20
Subhumid dry (MAR 1011 mm)				
Linga (typic haplusterts) (Nagpur, Maharashtra)	7.8	0.76	1	23
Bhatumbra (udic haplusterts) (Bidar, Karnataka)	10.1	0.90	4[b]	6
Semi-arid dry (MAR 842–583 mm)				
Jhalipura (typic haplusterts) (Kota, Rajasthan)	5.5	0.57	3.6[c]	01
Teligi (sodic haplusterts) (Bellary, Karnataka)	9.6	0.94	17[c]	24
Kovilpatti (gypsic haplusterts) (Thoothokudi, Tamil Nadu)	7.9	1.02	1[d]	33
Sollapuram (sodic haplusterts) (Anantapur, Andhra Pradesh)	17.5	1.32	18	2
Paral (sodic haplusterts) (Akola, Maharashtra)	10.4	1.48	14	4
Arid dry (MAR 533 mm)				
Sokhda (calcic haplusterts) (Rajkot, Gujarat)	21.7	2.12	28[b]	17

PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivitiy; MAR = mean annual rainfall.

[a] Data from Pal et al. (2003a); [b] Irrigated; [c] Ca-zeolitic; [d] Gypsic.

zeolitic (Ca-rich) vertisols can be comprehended through the following examples.

Scenario 1 – continuous use of the Purna river water of high salinity with low sodium hazards (C3-S1) (Richards, 1954) in non-zeolitic vertisols of Maharashtra (central India) has hastened the sodification process. In 7 years of irrigation, soils have become more calcareous by formation of 371 mg of $CaCO_3$ per 100 g of soil per year in the first 100 cm of the profile. Values of exchangeable sodium percentage (ESP) and sodium adsorption ratio (SAR) show a fourfold increase as compared with non-irrigated soils. Likewise, ionic composition and electrical conductivity of the saturation extract (ECe) show a two- to threefold increase. In addition, soils have become highly alkaline, and the sHC has further been impaired (Table 4.2). Such soils suffer waterlogging and salt-efflorescence appears on their surface.

Table 4.2. Comparative soil properties of unirrigated and irrigated deep black soils (haplusterts) of Maharashtra, India[a].

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) %	SAR	ESP	sHC (mm/h)
Unirrigated Chendkapur soils[b]						
0–17	8.3	2.3	6.1	3.5	3.8	3.2
17–44	8.4	1.5	6.9	2.9	3.4	2.7
44–67	8.5	1.9	8.3	3.1	3.6	2.3
67–100	8.6	2.4	12.6	3.4	3.9	2.0
100–130	8.6	1.9	13.9	3.6	4.2	1.3
Irrigated Chendkapur soils[b]						
0–15	8.9	5.7	10.4	18.2	17.8	3.1
15–43	8.9	6.5	10.9	20.7	18.2	3.2
43–59	8.8	5.2	11.8	18.7	15.3	3.2
59–93	8.6	3.4	12.3	11.6	11.6	0.9
93–129	8.6	3.2	12.7	7.9	7.0	0.9
Unirrigated Vasmat soils[c]						
0–18	3.2	0.94	21.5	–	4.0	26
18–45	3.2	2.50	17.7	–	4.6	34
45–77	0.9	2.64	17.4	–	5.5	35
77–108	0.9	1.85	15.8	–	6.0	33
108–142	9.2	0.67	17.2	–	5.5	13
142–166	9.2	0.32	17.2	–	3.9	12
Irrigated Vasmat soils[c]						
0–20	9.0	0.77	16.0	–	4.2	18
20–42	9.2	1.01	17.0	–	10.4	17
42–68	9.3	0.99	17.0	–	18.8	5
68–102	9.0	1.25	15.0	–	13.7	10
102–131	9.0	1.09	25.3	–	12.1	13
131–150+	9.0	1.02	16.1	–	8.0	12

[a]ECe = electrical conductivity of the saturation extract; SAR = sodium adsorption ratio; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity. [b]Data from Nimkar *et al.* (1992). [c]Data from Pal *et al.* (2003a).

Scenario 2 – there are Ca-zeolitic deep black soils in the semi-arid parts of Maharashtra (western India) that are being cultivated for sugarcane under canal irrigation for the last two decades. However, these soils lack salt-efflorescence on their surface and are not waterlogged at present. This may apparently suggest that these soils are not degraded. However, data for pH, ECe, $CaCO_3$ and ESP of unirrigated and irrigated black soils clearly indicate the development of soil sodicity in the latter soils (Table 4.2). The presence of Ca-zeolites, which ensure continuous supply of soluble Ca^{2+} ions, has prevented the decline of sHC from >10 mm/h to <10 mm/h (Pal *et al.*, 2006a). However, with time these soils will also become more calcareous, sodic and impermeable to water (Pal *et al.*, 2003a), which would impair their productivity.

Loss due to aridity

The following two examples would highlight how the lowering in MAR causes loss of soil productivity even in the presence of a soil modifier like gypsum.

Scenario 1 – deep black soils (vertisols) have limitations that constrain their full potential to grow both rainy-season and winter crops (NBSS&LUP–ICRISAT, 1991), as also reported from Nagpur, Amravati and Akola districts of Maharashtra state of central India. Either rainy-season crops or winter crops are grown in vertisols of the western part of Amravati district and adjoining Akola district, whereas they are grown in those of Nagpur district with limited irrigation (NBSS&LUP–ICRISAT, 1991). The mean monthly temperature is highest in Akola throughout the year by 0.5–1.5 °C. The MAR in

Akola, Amravati and Nagpur is 877 mm, 975 mm and 1127 mm, respectively. This indicates more aridity in Akola than in Amravati or Nagpur. Despite this fact, vertisols of these districts indicate similar soil moisture (typic tropustic) and temperature (hyperthermic) regimes (Balpande *et al.*, 1996). Under similar soil management by farmers in 29 vertisol areas, and also under similar soil moisture and temperature regimes, yields of cotton were better in soils of Nagpur than in those of Amravati and Akola (Table 4.3). The subsoils in the western part of Amravati and Akola districts are becoming sodic due to accelerated rate of formation and accumulation of PC (Kadu *et al.*, 2003). This impairs their sHC, and hence a significant positive correlation between yield of cotton and sHC has been observed (Kadu *et al.*, 2003).

Scenario 2 – under a rainfed situation, continuous efforts to grow deep-rooted crops like cotton, pigeonpea and sorghum in gypsum-containing vertisols of the semi-arid dry part of southern India indicates no development of sodicity in the profile. The soils have sHC >30 mm/h despite the rapid formation of PC (Table 4.4), unlike in zeolitic vertisols of the semi-arid climate. This may be attributed to much higher solubility of gypsum (30 me/l) than Ca-zeolites (<0.1 me/l) in distilled water (Pal *et al.*, 2006a). The gypsum in such soils acts as antagonistic to the formation of more soluble salts in the soil because it prevents clay dispersion. This favourable natural endowment has helped in making subsurface drainage in some such soils successful in removing the excess soluble salts (Danfors *et al.*, 1988) for sustaining crop production. The sustainability of crop productivity in these soils would, however, depend on the amount of gypsum in the soils. In its absence, these soils would become sodic and impermeable to both air and water. At present, despite having adequate sHC, these soils produce ~2 t/ha of cotton owing to erratically distributed MAR of 660 mm. These are the soils of the arid climates wherein irrigation may be of great help for some time in enhancing the crop productivity.

Management Interventions for Naturally Degraded Soils

The presence of $CaCO_3$ in sodic soils has generally been considered of doubtful significance in replacing exchangeable Na^+ ions by Ca^{2+} ions of $CaCO_3$ at a pH of around 8.4. However, it is greatly affected by other factors (Gupta and Abrol, 1990) such as application of gypsum followed by cropping in highly sodic

Table 4.3. Range in values of PC, ESP, sHC and yield of cotton in vertisols of Vidarbha, Maharashtra, central India[a].

District	Soil classification	PC (%)	ESP	sHC (mm/h) weighted mean in the profile (first 1 m)	Cotton yield (t/ha) (seed + lint)
Nagpur (MAR – 1011 mm)	Typic haplusterts/typic calciusterts (7/1 pedons)	3–6	0.5–11	4–18	1.0–1.8
Amravati (MAR – 975 mm)	Aridic haplusterts (11 pedons)	3–7	0.8–14	2–19	0.6–1.7
	Sodic haplusterts (8 pedons)	3–13	16–24	0.6–9.0	0.3–0.8
Akola (MAR – 877 mm)	Aridic haplusterts (1 pedon)	3–4	16–44	3–4	1.0
	Sodic haplusterts (1 pedon)	3–4	19–20	1–2	0.6

[a] Data from Division of Soil Resource Studies, NBSS&LUP, Nagpur, India. PC = pedogenic $CaCO_3$; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

Table 4.4. Physical and chemical properties of vertisols modified by the presence of gypsum in semi-arid dry parts of Tamil Nadu, India[a].

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) (%)	ESP	sHC (mm/h)
0–6	8.0	0.2	5.4	0.5	19
6–20	8.0	0.3	4.3	0.9	22
20–41	8.0	0.5	5.3	0.6	44
41–74	8.0	0.4	7.9	0.9	30
74–104	7.9	0.2	12.5	1.1	37
104–128	7.9	0.6	12.8	1.4	34
128–140	7.4	2.7	15.6	1.8	32
140+	7.5	–	17.4	0.3	48

[a] Data from Pal *et al.* (2003a). ECe = electrical conductivity of the saturation extract; ESP = exchangeable sodium percentage; sHC = saturated hydraulic conductivity.

soils (natrustalfs) of the IGP, and the application of gypsum increased the urease and dehydrogenase activity, the measures of biological activity, by about threefold (Rao and Ghai, 1985). Growing trees for more than a decade reclaimed the soil and improved the biological activity (Rao and Ghai, 1985). The reclamation was effected through more CO_2 production and mobilization of $CaCO_3$. The $CaCO_3$ content during the corresponding 12-year period decreased by 1%, 1.5% and nearly 2% with cereal cropping, grasses and agroforestry, respectively (Gupta and Abrol, 1990).

Changes in chemical properties were also observed in natrustalfs of the IGP where gypsum and rice cropping were followed for the reclamation of these soils (Sharma and Bhargava, 1981). After 30 months, there was an increase in exchangeable Ca^{2+} and Mg^{2+}, a decrease in ESP, pH, SAR, ECe, and soluble carbonates and bicarbonates, and also in native $CaCO_3$ to a considerable depth (Table 4.5). After 30 months of cultural practice, the dissolution of $CaCO_3$ (<2 mm) was 254 mg/100 g soil in the top 100 cm of the profile. Such reclamation technology also enhanced the OC content by about 64% as compared with original sodic soils. In addition, plantation of forest species not only improves the physical conditions of sodic soils but also helps in increasing OC content considerably (Swarup *et al.*, 2000).

Under rainfed conditions, the yield of deep-rooted crops in vertisols depends primarily on the amount of rain stored in the profile, and the extent to which this soil water is released during crop growth. In the semi-arid part of central India, rainfed cotton is grown under suboptimal conditions, with soil depth and moisture availability as the main limitations. Field experiments conducted in Yavatmal district of Maharashtra (central India) (Venugopalan *et al.*, 2004) on the comparison of soil properties of vertisols under organic and non-organic (conventional) cotton production systems indicate that the yields of cotton and component crops grown under the organic production system were higher than those of the non-organic production system and in general the productivity was higher than the average productivity of the district. Despite a hot, semi-arid tropical climate, higher values of OC (>0.6%) in the organic production system have been due to sequestration of carbon (Table 4.6) as compared with conventional system. Owing to improvement of OC and the subsequent dissolution of $CaCO_3$, the pH of soils under the organic production system remained below 8.1 (Table 4.6). In addition, the organic production system improved the availability of zinc (Table 4.6). It appears that adoption of the organic production system offers a viable alternative land use plan that not only enhances the OC content but also improves physical and chemical properties, arresting the formation of PC. The realization of the beneficial effects of modifiers like Ca-zeolites and gypsum in vertisols of dry climates in terms of improvement of their hydraulic properties (Pal *et al.*, 2006a) strongly suggests that application of such modifiers at the soil surface can restore the productivity of naturally degraded soils. There is evidence to this effect in the literature (Gupta and Abrol, 1990; Pal *et al.*, 2000).

Table 4.5. Chemical properties of untreated and gypsum-treated sodic soils[a].

Depth (cm)	pH (1:2 water)	ECe (dS/m)	$CaCO_3$ (<2 mm) (%)	SAR	ESP
Untreated soils					
0–13	10.3	8.3	1.0	90	79
13–29	10.4	8.9	2.1	93	97
29–59	10.0	4.8	1.8	88	45
59–89	9.6	2.5	1.0	93	32
89–116	9.6	2.5	1.2	74	15
116–160	9.6	–	4.6	8	13
Gypsum-treated soils					
0–14	8.6	1.2	0.8	12	6
14–31	9.1	1.4	1.2	31	16
31–62	9.4	2.0	1.0	55	8
62–88	9.4	2.0	0.9	61	17
88–121	9.5	2.0	2.7	75	14
121–165	9.6	2.3	6.9	56	14

[a] Data from Sharma and Bhargava (1981). ECe = electrical conductivity of the saturation extract; SAR = sodium adsorption ratio; ESP = exchangeable sodium percentage.

Table 4.6. Comparison of chemical properties of surface soils (0–20 cm) under organic and conventional production systems (based on 55 soil samples)[a].

	Conventional		Organic	
Properties	Range	Mean	Range	Mean
pH (1:2 water)	7.7–8.4	8.0	7.1–8.1	7.7
Organic carbon (%)	0.20–0.80	0.54	0.30–1.70	0.76
$CaCO_3$ (%)	2.4–12.2	6.2	1.1–12.5	5.3
Zn (mg/kg)	0.38–1.1	0.66	0.39–3.14	0.90
Soluble HCO_3 (me/l)	1.25–3.75	2.35	0.50–7.5	1.85

[a] Data from Venugopalan *et al.* (2004).

The above examples are a few specific management interventions in vogue in India to restore the productivity of degraded soils. Soil carbon dynamics as a robust parameter offers a unique opportunity in assessing the sustainability of the various cropping systems that are followed in India. The NBSS&LUP (ICAR), through organized research initiatives, sponsored by national and international organizations, developed a data set of soil OC and soil inorganic carbon for two important crop production zones, namely the IGP and the black soil region in the semi-arid tropics (SAT). The soil carbon data sets generated during 1980–2005 indicate that the agricultural practices in the IGP and black soil regions of SAT did not reduce SOC (soil organic carbon) content. The inorganic soil carbon estimated through the $CaCO_3$ deposition in these soils, however, increased over the 25-year period and thus forewarns of soil degradation (Bhattacharyya *et al.*, 2006a, 2007b,c).

Perspective

Amidst neotectonics and the global warming phenomenon, rising temperature and shrinking annual rainfall with erratic distribution pose perpetual threats for soils not only for the Indian subcontinent but also for soils of similar climatic and geologic conditions elsewhere. The rate of formation of $CaCO_3$ and concomitant development of subsoil sodicity in the soils of India provides a very realistic scenario as to how the semi-arid climatic conditions pose a threat to agriculture in a country with an unfavourable natural endowment, as it demands extra

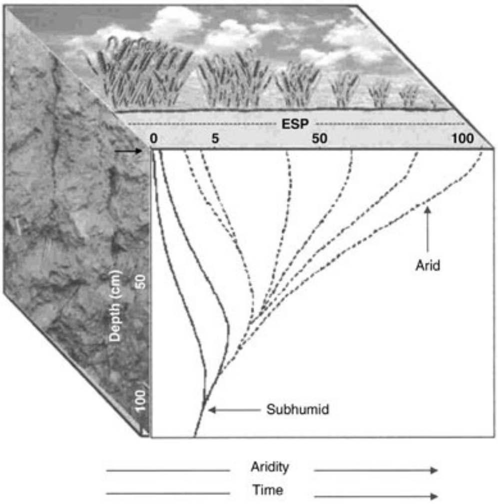


Fig. 4.7. A projected view of the progressive development of soil sodicity from wet to dry climates with time – a threat to Indian rainfed agriculture.

resources for raising crops (especially the winter crops) by the resource-poor farmers in the naturally degraded soils (Fig. 4.7). Thus, in the absence of national and international attention to combat this menace, soil degradation, through its impact on agricultural productivity, livelihood and environment, could lead to political and social instability. In addition, agricultural development would enhance the rate of deforestation, unwise use of marginal lands, accelerated run-off and soil erosion (Lal and Stewart, 1990).

The magnitude of degradation may not be very high in ferruginous soils at present, but it may create havoc in shrink–swell soils (vertisols and vertic intergrades) because of the huge amount of smectite clays. Perception of the natural degradation process may continue to be deceptive in shrink–swell and ferruginous soils as they lack evidence of salt-efflorescence on their surface (Pal *et al.*, 2000). However, the degradation process is proceeding at a much faster rate in soils of the IGP as compared with the other two soil types. Therefore, attempts to increase and stabilize yields in these soils, especially in soils without soil modifiers, by extension of canal irrigation may prove to be highly disastrous. This suggests that while managing natural resources for increasing soil productivity a new research initiative is required to comprehend and record the factors and processes of soil degradation whether natural or human induced, so that a precise cause–effect relationship is established. Such a relationship would form the mandatory requirement to develop methods to restore the productivity of already degraded soils and also to prevent the development of similar problem areas in the future.

Research initiatives on the significance of PC and soil modifiers like Ca-zeolites and gypsum in the management of naturally degraded soils, undertaken by the Central Soil Salinity Research Institute, Karnal, India (Abrol and Fireman, 1977) and NBSS&LUP (Srivastava *et al.*, 2002; Pal *et al.*, 2006a) suggest that for sustained performance of crops in soils of dry climates, the replenishment of Ca^{2+} ions both in the soil solution and in the exchange complex appears to be a viable technological intervention. The presence of $CaCO_3$ is of no significance and displacement of exchangeable Na^+ ions by Ca^{2+} ions from $CaCO_3$ is not feasible in soils with pH >8.0. If there are rootlets in the soil through which the rainwater passes, or other sources of CO_2 production and accumulation, there will be a corresponding increase in solubility of PC and a lowering of equilibrium pH. This situation can be further enhanced in the presence of Ca-zeolites and gypsum during the cultivation of crops (Pal *et al.*, 2000, 2006a). This way, such soils can be made resilient, where not only the movement of water but also the release of water during crop growth can be enhanced.

References

Abrol, I.P. and Chaudhury, T.N. (1988) Impact of irrigation on productivity of shrink-swell soils. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Classification, Management and Use Potential of Shrink-Swell Soils*, INWOSS, 24–28 October 1988. National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India; and Oxford and IBH Publishing Co., New Delhi, India, pp. 7–14.

Abrol, I.P. and Fireman, M. (1977) *Alkali and Saline Soils; Identification and Improvement for Crop Production*. Bulletin No. 4. Central Soil Salinity Research Institute, Karnal, India.

Agarwal, R.R. and Mehrotra, C.LO. (1953) *Soil Survey and Soil Work in Uttar Pradesh*, Vol. III. Department of Agriculture, Uttar Pradesh, India.

Ahmad, N. (1996) Occurrence and distribution of vertisols. In: Ahmad, N. and Mermut, A. (eds) *Vertisols and Technologies for their Management*. Elsevier, Amsterdam, the Netherlands, pp. 1–41.

Anonymous (1984) *Western Ghats Region, Maharashtra Subregional Plan*. Regional Planning Division, Town and Country Planning Organization, Ministry of Works and Housing, Government of India.

Balpande, S.S., Deshpande, S.B. and Pal, D.K. (1996) Factors and processes of soil degradation in vertisols of the Purna Valley, Maharashtra, India. *Land Degradation & Development* 7, 313–324.

Bhattacharyya, T., Pal, D.K. and Deshpande, S.B. (1993) Genesis and transformation of minerals in the formation of red (alfisols) and black (inceptisols and vertisols) soils on Deccan basalt in the Western Ghats, India. *Journal of Soil Science* 44, 159–171.

Bhattacharyya, T., Pal, D.K. and Srivastava, P. (1998) Role of zeolites in persistence of high altitude ferruginous alfisols of the humid tropical Western Ghats, India. *Geoderma* 90, 263–276.

Bhattacharyya, T., Pal, D.K., Chandran, P. and Ray, S.K. (2005) Land use, clay mineral type and organic carbon content in two mollisols–alfisols–vertisols catenary sequences of tropical India. *Clay Research* 24, 105–122.

Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Pal, D.K., Venugopalan, M.V., Durge, S.L., Srivastava, P., Dubey, P.N., Kamble, G.K., Sharma, R.P., Wani, S.P., Rego, T.J., Ramesh, V. and Manna, M.C. (2006a) Estimation of carbon stocks in red and black soils of selected benchmark spots in semi-arid tropics of India. *Global Theme on Agroecosystems Report No. 28*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 402 324, Andhra Pradesh, India.

Bhattacharyya, T., Chandran, P., Ray, S.K., Mandal, C., Pal, D.K., Venugopalan, M.V., Durge, S.L., Srivastava, P., Dubey, P.N., Kamble, G.K., Sharma, R.P., Wani, S.P., Rego, T.J., Ramesh, V. and Manna, M.C. (2006b). Morphological properties of red and black soils of selected benchmark spots in semi-arid tropics of India. *Global Theme on Agroecosystems, Report No. 21*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Bhattacharyya, T., Pal, D.K., Chandran, P., Ray, S.K., Durge, S.L., Mandal, C., Telpande, B. and Wani, S.P. (2007a) Available ‘K’ reserve of two major crop growing regions (alluvial and shrink-swell soils) in India. *Indian Journal of Fertilizers* 3, 41–52.

Bhattacharyya, T., Pal, D.K., Easter, M., Batjes, N.H., Milne, E., Gajbhiye, K.S., Chandran, P., Ray, S.K., Mandal, C., Paustian, K., Williams, S., Killian, K., Coleman, K., Falloon, P. and Powlson, D.S. (2007b) Modelled soil organic carbon stocks and changes in the Indo-Gangetic Plains, India from 1980 to 2030. *Agriculture Ecosystems and Environment* 122, 84–94.

Bhattacharyya, T., Pal, D.K., Easter, M., Williams, S., Paustian, K., Milne, E., Chandran, P., Ray, S.K., Mandal, C., Coleman, K., Falloon, P., Powlson, D.S. and Gajbhiye, K.S. (2007c) Evaluating the Century C model using long-term fertilizer trials in the Indo-Gangetic Plains, India. *Agriculture Ecosystems and Environment* 122, 73–83.

Bhumbla, D.R., Abrol, I.P., Bhargava, G.P. and Singla, S.K. (1973) *Soils of the Experimental Farm, Karnal*. Central Soil Salinity Research Institute, Karnal, Haryana, India.

Brewer, R. (1976) *Fabric and Mineral Analysis of Soils*. Robert E. Krieger Publishing Co., Huntington, New York, USA.

Brunner, H. (1970) Pleisitozane klimaschwankengen im Bereich den ostlichen Mysore-Plateaus (Sudindien). *Geologie* 19, 72–82.

Chandran, P., Ray, S.K., Bhattacharyya, T., Krishnan, P. and Pal, D.K. (2000) Clay minerals in two ferruginous soils of southern India. *Clay Research* 19, 77–85.

Danfors, E., Ramanathan, G. and Kandaswamy, P. (1988) Swelling clays of vertisols in PAP Command area and drainage problems. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Proceedings of the International Workshop on Swell–Shrink Soils*. Oxford and IBH Publishing Co., New Delhi, India, pp. 15–19.

Deotare, B.C. (2006) Late Holocene climatic change: archaeological evidence from the Purna Basin, Maharashtra. *Journal of the Geological Society of India* 68, 517–526.

Dudal, R. (1965) Dark clay soils of tropical and subtropical regions. FAO Agriculture Development Paper 83, Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

Eswaran, H. and van den Berg, E. (1992) Impact of building of atmospheric CO_2 on length of growing season in the Indian sub-continent. *Pedologie* 42, 289–296.

Eswaran, H., Kimble, J. and Cook, T. (1988) Properties, genesis and classification of vertisols. In: Hirekerur, L.R., Pal, D.K., Sehgal, J.L. and Deshpande, S.B. (eds) *Classification, Management and Use Potential of Swell–Shrink Soils,* INWOSS, 24–28 October 1988. National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur, India; and Oxford and IBH Publishing Co., New Delhi, India, pp. 1–22.

Eswaran, H., Kimble, J., Cook, T. and Beinroth, F.H. (1992) Soil diversity in the tropics: implications for agricultural development. SSSA Special Publication No. 29. Soil Science Society of America, Inc., and American Society of Agronomy, Inc. Madison, Wisconsin, USA.

FAO (Food and Agriculture Organization of the United Nations) (1994) *Land Degradation in South Asia: its Severity, Causes and Effects upon the People*. World Soil Resources Reports 78. FAO, Rome, Italy.

Gaur, V.K. (1994) Evaluation of seismic hazard in India towards minimizing earthquake risk. *Current Science* 67, 324–329.

Ghatak, S., Ghatak, M., Roy, A. and Chakrabarti, A. (2005) A preliminary overview of tectonic-climatic feedback in Purna Basin at south Satpura foothills: future research needs. IGCP-476, Extended Abstract Volume Paper, Geological Survey of India, Central Region, Nagpur, India, pp. 21–26.

Gupta, R.K. and Abrol, I.P. (1990) Salt-affected soils: their reclamation and management for crop production. In: Stewart, B.A. (ed.), *Advances in Soil Science*, Vol. II. Springer-Verlag, Berlin, Germany, pp. 223–288.

Hall, G.F., Daniels, R.B. and Foss, J.E. (1982) Rates of soil formation and renewal in the USA. In: Schmidt, B.L. (ed.) *Determinants of Soil Loss Tolerance*. ASA Publication No. 45. American Society of Agronomy, Madison, Wisconsin, USA, pp. 23–29.

Kadu, P.R., Vaidya, P.H., Balpande, S.S., Satyavathi, P.L.A. and Pal, D.K. (2003) Use of hydraulic conductivity to evaluate the suitability of vertisols for deep rooted crops in semi-arid parts of Central India. *Soil Use & Management* 19, 208–216.

Kalbande, A.R., Pal, D.K. and Deshpande, S.B. (1992) b-Fabric of some benchmark vertisols of India in relation to their mineralogy. *Journal of Soil Science* 43, 375–385.

Kumar, S., Parkash, B., Manchanda, M.L., Singhvi, A.K. and Srivastava, P. (1996) Holocene landform and soil evolution of the western Gangetic Plains: implications of neotectonics and climate. *Zeitschrift fur Geomorphologie N.F.*, Supplement, 103, 283–312.

Lal, R. and Stewart, B.A. (1990) Soil degradation: a global threat. In: Lal, R. and Stewart, B.A. (eds) *Advances in Soil Science*, Vol. II. Springer-Verlag, Berlin, pp. 13–17.

Lal, R., Hall, G.F. and Miller, F.P. (1989) Soil degradation. I. Basic processes. *Land Degradation and Rehabilitation* 1, 51–69.

Mermut, A.R. and Dasog, G.S. (1986) Nature and micromorphology of carbonate glaebules in some vertisols of India. *Soil Science Society of America Journal* 50, 382–391.

Mohindra, R., Parkash, B. and Prasad, J. (1992) Historical geomorphology and pedology of the Gandak Megafan, Middle Gangetic Plain, India. *Earth Surface Process Landforms* 17, 643–662.

Mohr, E.C.J., Van Baren, F.A. and Van Schuylenborgh, J. (1972) *Tropical Soils – a Comprehensive Study of their Genesis*. Mouton-Ichtiarbaru – Van Hoeve, The Hague, the Netherlands.

NBSS&LUP–ICRISAT (National Bureau of Soil Survey and Land Use Planning–International Crops Research Institute for the Semi-arid Tropics) (1991) *The Suitabilities of Vertisols and Associated Soils for Improved Cropping Systems in Central India*. NBSS&LUP, Nagpur, India and ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

Nimkar, A.M., Deshpande, S.B. and Babrekar, P.G. (1992) Evaluation of salinity problem in swell-shrink soils of a part of the Purna Valley, Maharashtra. *Agropedology* 2, 59–65.

Oldeman, L.R. (ed.) (1988) *Global Assessment of Soil Degradation (GLASOD)*. Guidelines for general assessment of status of human-induced soil degradation. ISRIC, Wageningen, the Netherlands.

Pal, D.K., Deshpande, S.B., Venugopal, K.R. and Kalbande, A.R. (1989) Formation of di- and trioctahedral smectite as an evidence for paleoclimatic changes in southern and central Peninsular India. *Geoderma* 45, 175–184.

Pal, D.K., Dasog, G.S., Vadivelu, S., Ahuja, R.L. and Bhattacharyya, T. (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. In: Lal, R., Kimble, J.M., Eswaran, H. and Stewart, B.A. (eds) *Global Climate Change and Pedogenic Carbonates*. Lewis Publishers, Boca Raton, Florida, USA, pp. 149–185.

Pal, D.K., Balpande, S.S. and Srivastava, P. (2001) Polygenetic vertisols of the Purna Valley of central India. *Catena* 43, 231–249.

Pal, D.K., Bhattacharyya, T., Ray, S.K. and Bhuse, S.R. (2003a) Developing a model on the formation and resilience of naturally degraded black soils of the peninsular India as a decision support system for better land use planning. NRDMS, DST Project Report. Nagpur, India.

Pal, D.K., Srivastava, P. and Bhattacharyya, T. (2003b) Clay illuviation in calcareous soils of the semi-arid part of the Indo-Gangetic Plains, India. *Geoderma* 115, 177–192.

Pal, D.K., Srivastava, P., Durge, S.L. and Bhattacharyya, T. (2003c) Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangetic Plains, India. *Catena* 51, 3–31.

Pal, D.K., Bhattacharyya, T., Ray, S.K., Chandran, P., Srivastava, P., Durge, S.L. and Bhuse, S.R. (2006a) Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded vertisols of the peninsular India in redefining the sodic soils. *Geoderma* 136, 210–228.

Pal, D.K., Bhattacharyya, T., Srivastava, P., Chandran, P. and Ray, S.K. (2006b) Soils of the Indo-Gangetic Plains, India: their historical perspective and management. Presented at the 18th World Congress of Soil Science, 9–15 July 2006, Philadelphia, USA.

Parkash, B., Kumar, S., Rao, M.S., Giri, S.C., Kumar, C.S., Gupta, S. and Srivastava, P. (2000) Holocene tectonic movements and stress field in the Western Gangetic Plains. *Current Science* 79, 438–449.

Pascoe, E.H. (1965) *A Manual of the Geology of India and Burma*. Managers of Publication, Delhi, India.

Prasad, C.R. and Gadgil, S. (1986) Climatic change – a global perspective. *Science Age* 4, 35–40.

Rajaguru, S.N. and Korisettar, R. (1987) Quaternary geomorphic environment and culture succession in Western India. *Indian Journal of Earth Sciences* 14, 349–361.

Randhawa, M.S. (1945) Progressive dessication of northern India in historical times. *Journal of Bombay National Historical Society* 45, 558–565.

Rao, D.L.N. and Ghai, S.K. (1985) Urease and dehydrogenase activity of alkali and reclaimed soils. *Australian Journal of Soil Research* 23, 661–665.

Ray, S.K., Bhattacharyya, T., Chandran, P., Sahoo, A.K., Sarkar, D., Durge, S.L., Raja, P., Maurya, UK and Pal, D.K. (2006) On the formation of cracking clay soils (vertisols) in West Bengal. *Clay Research* 25, 141–152.

Rengasamy, P., Sarma, V.A.K., Murthy, R.S. and Murti, G.S.R.K. (1978) Mineralogy, genesis and classification of ferruginous soils of the eastern Mysore Plateau, India. *Journal of Soil Science* 29, 431–445.

Richards, L.A. (ed.) (1954) *Diagnosis and Improvement of Saline and Alkali Soils. USDA Agriculture Handbook 60*. USDA, Washington, DC, USA.

Ritter, D.F. (1996) Is Quaternary geology ready for the future? *Geomorphology* 16, 273–276.

Sahasrabudhe, Y.S. and Deshmukh, S.S. (1981) Laterites of the Maharashtra State. In: *Proceedings of the International Seminar on Laterization Processes*. A.A. Balkema, Rotterdam, the Netherlands, pp. 209–220.

Sehgal, J.L. (1998) Red and lateritic soils: an overview. In: Sehgal, J., Blum, W.E. and Gajbhiye, K.S. (eds) *Managing Red and Lateritic Soils for Sustainable Agriculture*, Vol. I. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India.

Sehgal, J.L. and Abrol, I.P. (1992) Land degradation status: India. *Desertification Control Bulletin* 21, 24–31.

Sehgal, J.L. and Abrol, I.P. (1994) *Soil Degradation in India: Status and Impact*. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India.

Sehgal, J.L., Hall, G.P. and Bhargava, G.P. (1975) An appraisal of the problems in classifying saline-sodic soils of the Indo-Gangetic plains in NW India. *Geoderma* 14, 75–91.

Sharma, R.C. and Bhargava, G.P. (1981) Morphogenic changes in an alkali (sodic) soil pedon during amelioration through gypsum application. *Journal of the Indian Society of Soil Science* 29, 274–277.

Singh, G., Joshi, R.D. and Singh, A.B. (1972) Stratigraphic and radiocarbon evidence for the age and development of the three salt lake deposits in Rajasthan, India. *Quaternary Research* 2, 496–505.

Singh, G., Joshi, R.D., Chopra, S.K. and Singh, A.B. (1974) Late Quaternary history of vegetation and climate of Rajasthan desert, India. *Philosophical Transactions of the Royal Society of London* 267, 467–501.

Singh, G., Wasson, R.J. and Agarwal, D.P. (1990) Vegetation and seasonal climate changes since the last full glacial in the Thar desert, NW India. *Review of Paleobotany and Palynology* 64, 351–358.

Singh, L.P., Parkash, B. and Singhvi, A.K. (1998) Evolution of the Lower Gangetic Plain landforms and soils in West Bengal, India. *Catena* 33, 75–104.

Singh, S., Parkash, B., Rao, M.S., Arora, M. and Bhosle, B. (2006) Geomorphology, pedology and sedimentology of the Deoha/Ganga-Ghghara Interfluve, Upper Gangetic Plains (Himalayan Foreland Basin) – extensional tectonic implications. *Catena* 67, 183–203.

Soil Survey Staff (1999) *Soil Taxonomy: a Basic System of Soil Classification for Making and Interpreting Soil Surveys*. Agricultural Handbook, Vol. 436. USDA, Washington, DC, USA.

Srivastava, P., Parkash, B., Sehgal, J.L. and Kumar, S. (1994) Role of neotectonics and climate in development of the Holocene geomorphology and soils of the Gangetic Plains between Ramganga and Rapti rivers. *Sedimentary Geology* 94, 129–151.

Srivastava, P., Parkash, B. and Pal, D.K. (1998) Clay minerals in soils as evidence of Holocene climatic change, central Indo-Gangetic Plains, north-central India. *Quaternary Research* 50, 230–239.

Srivastava, P., Chandran, P., Ray, S.K. and Bhattacharyya, T. (2001) Evidence of chemical degradation in tropical ferruginous soils of southern India. *Clay Research* 20, 31–41.

Srivastava, P., Bhattacharyya, T. and Pal, D.K. (2002) Significance of the formation of calcium carbonate minerals in the pedogenesis and management of cracking clay soils (vertisols) of India. *Clays and Clay Minerals* 50, 111–126.

Subramanian, K.S. and Mani, G. (1981) Genetic and geomorphic aspects of laterites on high and low landform in parts of Tamil Nadu, India. In: *Proceedings of the International Seminar on Laterization Processes*. A.A. Balkema, Rotterdam, the Netherlands, pp. 236–245.

Swarup, A., Manna, M.C. and Singh, G.B. (2000) Impact of landuse and management practices on organic carbon dynamics in soils of India. In: Lal, R., Kimble, J.M., Eswaran, H. and Stewart, A. (eds) *Global Climate Change and Tropical Ecosystems*. Lewis Publishers, Boca Raton, Florida, USA, pp. 261–281.

UNEP (1992) *World Atlas of Desertification*. Edward Arnold, London, UK.

Vaidya, P.H. and Pal, D.K. (2002) Microtopography as a factor in the degradation of vertisols in central India. *Land Degradation & Development* 13, 429–445.

Venugopalan, M.V., Chandran, P., Pal, D.K., Challa, O. and Durge, S.L. (2004) Effect of organic and conventional cotton production systems on soil properties: a case study in Yavatmal district, Maharashtra. *International Symposium on Strategies for Sustainable Cotton Production – a Global Vision*, Vol. II, *Crop Production*. 22–25 November 2004, University of Agricultural Sciences, Dharwad, Karnataka, India, pp. 118–121.

5 Determinants of Crop Growth and Yield in a Changing Climate

P.K. Aggarwal
Indian Agricultural Research Institute, New Delhi 110 012, India;
email: pkaggarwal.iari@gmail.com

Introduction

The world population has crossed 6.7 billion; almost 20% of these people live in South Asia. The population of the world, especially of South Asia, continues to increase, even now, at a significant rate. This rapid and continuing increase in population implies a greater demand for food. Rice production in Asia alone must increase to more than 800 million t over the next 20 years (Hossain, 1995). Cereal requirements of India alone by 2020 will be between 257 and 374 million t (Rosegrant *et al.*, 1995; Kumar, 1998; Bhalla *et al.*, 1999). Demand for pulses, fruits, vegetables, milk, meat, eggs and marine products is also expected to increase very sharply. This additional food will have to be produced from the same, or even a shrinking, land resource base because there is no additional land available for cultivation.

Although the world as a whole has sufficient food for everyone and perhaps will continue to have in future as well, the widespread poverty in many countries prevents access to food. Today, even after several 'revolutions' in agriculture, almost 800 million people, who almost entirely live in the developing world, go hungry (FAO, 2006). About two-thirds of the undernourished in the world live in Asia. In the 21st century, one of the great challenges will be to ensure that food production is coupled with both poverty reduction and environmental protection.

The Intergovernmental Panel on Climate Change (IPCC), in its recently released report (IPCC, 2007a), has reconfirmed that the earth's temperature has increased by 0.74° C between 1906 and 2005. There is also a global trend for increased frequency of droughts, as well as heavy precipitation events over most land areas. Cold days, cold nights and frost have become less frequent, while hot days, hot nights and heat-waves have become more frequent. The IPCC has projected that the temperature increase by the end of this century is likely to be in the range 1.5 to 4.0 °C. It is also likely that in future tropical cyclones will become more intense, with larger peak wind speeds and heavy precipitation. Himalayan glaciers and snow cover are projected to contract. Increases in the amount of precipitation are very likely in high latitudes, while decreases are likely in most subtropical land regions.

Such global climatic changes will affect agriculture through their direct and indirect effects on crops, soils, livestock and pests. Global studies have indicated a loss of 5–40% cereal production by 2100 AD due to global warming, threatening the food security of several countries (Rosenzweig and Parry, 1994; Easterling *et al.*, 2007). Thus, there is a tremendous challenge facing agricultural scientists to develop technologies for increasing food production in the coming decades. There is an urgent need to secure the past yield gains and further increase the potential yield of major food crops.

Rainfed Agriculture: Unlocking the Potential
(eds S.P. Wani *et al.*)

High potential crop yields can be achieved/realized in future either by reducing yield gaps or by raising yield potential. For example, the potential yields of rice and wheat are calculated to be more than 6 t/ha in India whereas their average yields range between 2 and 3 t/ha (Aggarwal *et al.*, 2000). Such large yield gaps can be tapped in future for ensuring food security in the scenario of adverse climatic impacts. Institutional support in the form of improved extension services, markets and infrastructure needs to be provided in such regions to increase stability and bridge yield gaps. Raising yield potential is, however, important for regions where yields are already high and are stagnating, such as in Punjab, India.

Determination of the productivity potential of a crop requires a thorough understanding of crop growth and development. These, in turn, are dependent upon several climatic, edaphic, hydrological, physiological and management factors. The major factors affecting crop growth and development are radiation, temperature (yield determining), water, nutrition (yield limiting), and pests and diseases (yield reducing) (Van Ittersum and Rabbinge, 1997). In addition, productivity is also determined by many other factors, such as cultivar, its physiology and crop management, which interact with weather and soils to influence yield level. In irrigated and well-managed crops, productivity is primarily determined by radiation and temperature, whereas in rainfed areas, rainfall and soil moisture storage are of prime importance. In this chapter, our objective is to discuss the key determinants of crop growth and yield in a global scenario of changing climate.

Key Determinants of Crop Growth and Yield

Crop–climate interactions

Atmospheric carbon dioxide (CO_2) concentration has reached 381 ppm today, from a low level of 280 ppm in 1750 AD. It is now rising at a rate of 1.8–2.0 ppm per year (IPCC, 2007a). Increase in atmospheric CO_2 has a fertilization effect on crops with a C_3 photosynthetic pathway and thus promotes their growth and productivity. The C_4 crops are not known to significantly benefit from further CO_2 increase. Increased CO_2 also results in increased water use efficiency of all crops. Under field conditions, however, response to enhanced CO_2 is moderated by other environmental constraints. Long *et al.* (2006) have recently shown that the yield enhancement with high CO_2 is only to the extent of 10–15% in field-grown cereal crops, as against 20–30% response documented earlier (Kimball *et al.*, 2002). Using a crop model, Aggarwal (2003) showed that the benefit of enhanced CO_2 was moderated by nutrient and water constraints in wheat.

Several approaches have been tried earlier by scientists to raise yield potential through manipulation of source and/or sink. The International Rice Research Institute (IRRI) has been trying to develop a new plant type of rice, with a yield potential 20–25% higher than that of existing semi-dwarf rice varieties, through ideotype breeding approaches (Khush, 1995) for tropical environments. The proposed plant type has a low tillering capacity (three to four tillers when direct-seeded), few unproductive tillers, 200–250 grains per panicle, a plant height of 90–100 cm, thick and sturdy stems, leaves that are thick, dark green and erect, a vigorous root system, 100–130 days growth duration and increased harvest index (Peng *et al.*, 1994). However, these did not yield well because of limited biomass production and poor grain filling (Peng and Khush, 2003).

Increase in temperature, depending upon the current ambient temperature, can reduce crop duration, increase crop respiration rates, alter photosynthate partitioning to economic products, affect the survival and distribution of pest populations thus developing a new equilibrium between crops and pests, hasten nutrient mineralization in soils, decrease fertilizer use efficiencies and increase evapotranspiration. The stages of growth at which weather extremes occur is important in determining yield losses. For example, a temperature increase for a short period around pollen formation, dispersal and germination can lead to partial/complete sterility in crops (Horie, 1993).

Depending upon the current temperatures and thresholds, increased temperature can sometimes result in yield increase. Easterling *et al.* (2007) have shown that an increase in temperature of up to 3 °C could result in increased yields of cereals in temperate environments, whereas in tropical countries yields could start decreasing with a small increase in temperature. This has implications on global food trade. It is expected that due to rising food demands and decreased production associated with global warming in tropical countries, trade flows of food would increase from temperate countries to tropics. Fischer *et al.* (2002b) estimate that by 2080 cereal imports by developing countries would rise by 10–40%.

Rainfall, and hence availability of water, is the major limiting factor in the growth and production of crops worldwide. Plants need adequate moisture, especially during critical stages of germination and fruit development. Irrigation systems have been developed around the world by many countries to ensure crop water supply. However, despite this, large areas still remain rainfed. In climate change scenarios, globally precipitation is likely to increase, with large spatial and temporal variation. These changes in precipitation, especially increased frequency of heavy rainfall events, would lead to increased probability of droughts and floods, in turn, affecting food production stability.

Frost causes significant damage to crops, especially to cruciferous and solanaceous crops such as mustard and potato in higher latitudes. Increasing trends in minimum temperatures in future can alleviate this stress in several regions and thus increase yields.

Changes in productivity due to climatic change can also result in geographical shifts of agriculture. This could be accelerated by shifts in the virulence of pathogens and insects. Newman (1980) showed that a 1 °C increase in mean annual temperature could shift the US corn (maize) belt by approximately 100 km. Carter and Saarikko (1996) showed a similar poleward shift in Finnish cereal cultivation by 100–150 km for each 1 °C increase in mean annual temperature. Aggarwal *et al.* (1995) also showed that wheat cultivation in India is likely to shift northwards with climate change.

Several adaptation strategies can alter crop–climate interactions and thus reduce the adverse impacts on agriculture. Farmers and societies have been increasing their adaptive capacities to changing environments, depending on technological and financial capabilities. For example, establishment of buffer food stocks and agricultural insurance schemes, and development of irrigation infrastructure have been strengthened earlier by many countries to increase their adaptive capacity to climatic extremes such as droughts and floods. Many countries have the historical experience of dealing with climatic variability; climate change may, however, increase its dimensions to outside the range of previous experiences. Potential adaptation strategies for agriculture to mitigate climate change have been suggested which could be implemented by the farmers themselves (Aggarwal *et al.*, 2004; Easterling *et al.*, 2004). These include diversification to more-adapted crops and varieties, changing planting dates, and improving water and fertilizer management. Easterling *et al.* (2007) showed that the benefits of adaptation vary with crops, regions and temperature changes. In general, such adaptations lead to damage avoidance in grain yields of cereals crops caused by a temperature increase of up to 1.5–3 °C in tropical regions and 4.5–5 °C in temperate regions.

Water availability

One of the significant impacts of global warming is on water resources. This is due to spatially variable changes in precipitation, increased rate of glacier melt and retreat affecting river water flows, greater evaporation due to increase in temperature and higher water demand. These changes are likely to affect all aspects of agricultural water management including irrigation availability, soil moisture, evapotranspiration and run-off.

The balance among precipitation, evaporation, run-off and soil drainage determines soil moisture. Climate variability, interseasonal as well as annual, is known to affect water levels in aquifers. Changes in temperature and precipitation associated with global warming will alter recharge to groundwater aquifers, causing shifts in water table levels (IPCC, 2001). Increase in sea levels may also lead to salinity intrusion in coastal aquifers. In several regions such as South Asia, it is projected that the rainfall intensity may increase. Such changes may result in higher run-off and hence less groundwater recharge.

Arnell (2004) and Nohara *et al.* (2006) simulated the change in run-off in various parts of the world under different scenarios of climate change. Their results showed an increased run-off in high latitudes and the wet tropics, and decreased run-off in mid-latitudes and some parts of the dry tropics. Consequent declines in water availability are therefore projected to affect some of the areas currently suitable for rainfed crops (Easterling *et al.*, 2007).

The increased melting and recession of glaciers associated with global climate change could further change the run-off scenario. The IPCC in its recent report has shown that glaciers all over the world are receding at a rapid rate (IPCC, 2007a). In recent decades, Himalayan glaciers have receded between 2.6 and 28 m/year (Kulkarni and Bahuguna, 2002). Mass balance studies indicate significant increase in glacial degraded run-off volume in the last decade, from 200 mm in 1992 to 455 mm in 1999 (Dobhal *et al.*, 2004).

With 70% of the global water withdrawals and 90% of the global water consumption, the irrigation sector is the dominant water use sector at the global scale. According to an FAO (Food and Agriculture Organization of the United Nations) projection of agriculture in developing countries (Bruinsma, 2003), the developing countries would like to expand their irrigated area by 20% by 2030. Most of this expansion will occur in already water-stressed areas, such as South Asia and North Africa. Such an analysis does not consider increased irrigation requirements due to global-warming-associated increase in evaporative demand. Doll (2002) projected significant change in the net irrigation requirements for the global scale due to climatic changes. Depending on emissions scenario and climate model, global net irrigation requirements were found to increase by 1–3% until 2025 and by 2–7% until 2075. Fischer *et al.* (2006) computed increases in global net irrigation requirements of 20% by 2080, with large spatial variations. Predicted increased variability of precipitation, which includes longer drought periods, would also lead to an increase in irrigation requirements, even if the total precipitation during the growing season remained the same (Eheart and Tornil, 1999).

The above results show that irrigation requirement may increase in future. In contrast, we can expect in future a scenario of reduced water supply for agriculture due to the effects of global climatic changes on the hydrological cycle, increasing competition from industry/urban areas, and currently declining trends of groundwater tables. Production of an increased quantity of food with decreasing availability of quality irrigation water would, therefore, be a big challenge for the agricultural community.

Soil suitability

Changes in precipitation patterns and amount, and temperature can influence soil water content, run-off and erosion, workability, temperature, salinization, biodiversity, and organic carbon and nitrogen content (Van Ittersum *et al.*, 2003; Nearing *et al.*, 2004). Changes in soil water induced by global climate change may affect all soil processes and ultimately crop growth. Increase in temperature would also lead to increased evapotranspiration, which may result in lowering of the groundwater table at some places. Increased temperature coupled with reduced rainfall enhances upward water movement, leading to accumulation of salts in upper soil layers. Similarly, rise in sea level associated with increased temperature may lead to saltwater ingression in the coastal lands, making them unsuitable for conventional agriculture.

The contribution of agriculture globally to greenhouse gas emissions is 13.5% (IPCC, 2007b), although there are large regional variations. Mitigating emission of greenhouse gases is today a global priority. Even though the contribution of agriculture is small, there are options available that can assist in reducing greenhouse gas emissions. Improved water and fertilizer management in rice fields, use of nitrification inhibitors such as neem-coated urea and efficient use of energy are some examples. Increasing the area under biofuels and agroforestry could also mitigate greenhouse gas emissions. However, this may have trade-offs with the goal of increasing food production.

Rapidly increasing demand for biofuels in North America and Europe is making fundamental changes to agricultural markets and is likely to keep the prices of agricultural commodities high over the next decade, according to a recent report by the Organization for Economic Cooperation and Development (OECD) and the

FAO (OECD–FAO, 2007). The study indicates that in the next 10 years (2009 onwards), substantial amounts of maize in the USA, wheat and rapeseed in the EU and sugar in Brazil will be used for ethanol and biodiesel production. It also indicates that high demand for biofuel feedstocks, such as cereals, sugar, oilseeds and vegetable oils, is likely to contribute to a 20–50% rise in international commodity prices over the next 10 years, in comparison with the 1997–2007 average. At the same time, the surging use of maize and other cereals for biofuel production decreases their availability for food, industry and poultry. There is considerable interest in growing more biofuels even in developing countries that are generally short of food.

Recent researches have shown that surface seeding or zero tillage establishment of upland crops after rice gives similar yields to those planted under normal conventional tillage over a diverse set of soil conditions. This reduces the cost of production, allows earlier planting and thus higher yields, results in less weed growth, reduces the use of natural resources such as fuel and steel for tractor parts, and shows improvements in efficiency of water and fertilizers (RWC–CIMMYT, 2003). In addition, such resource-conserving technologies restrict release of soil carbon, thus mitigating increase of CO_2 in the atmosphere. It is estimated that zero tillage saves at least 30 l of diesel as compared with conventional tillage. This leads to 80 kg/ha/year reduction in CO_2 production (Grace *et al.*, 2003). If this saving could be translated even partially to large arable areas, substantial CO_2 emissions to the atmosphere could be reduced.

Crop–pest interactions

It is estimated that insect pests, pathogens and weeds result in almost 30% loss in crop production at present. Avoidance of such loss constitutes one of the main sources of sustainability in crop production. Change in climate may bring about changes in population dynamics, growth and distribution of insects and pests. Besides having a significant direct influence on the pest population build-up, the weather also affects the pest population indirectly through its effects on other factors like food availability, shelter and natural enemies (Chakraborty and Datta, 2003; Cocu *et al.*, 2005; Salinari *et al.*, 2006).

Aphid is a major pest of wheat and its occurrence is highly influenced by weather conditions. Cloudy weather with high relative humidity favours the occurrence of aphids in the field. Under most favourable conditions, a population density of 1000 million/ha in a wheat field has been reported. Weather changes may lead to aphid occurrence at the very juvenile and more susceptible stage of the crop, leading to tremendous loss. In nature, aphids are checked by *Coccinella septumpunctata*, and in the case where the weather limits *Coccinella*'s growth, the production losses could be further magnified. With small changes, the virulence of different pests changes. For example, at 16 °C, the length of latent period is small for yellow rust. Once the temperature goes beyond 18 °C, this latent period increases but that of yellow and stem rusts decreases. Appearance of black rust in north India in the 1960s and 1970s was related to the temperature-dependent movement of spores from south to north India. Thus, any small change in temperature can result in changed virulence as well as appearance of new pests in a region.

Several pathogens such as *Phytophtora* and *Puccinia* group produce abundant propagules from the infected lesion or spot. Invariably they also possess a very short incubation cycle or life cycle period. Such pathogens and pests are highly sensitive to even minor changes in temperature, humidity and sunlight. Any change in the weather conditions that further reduce the incubation period will result in the completion of more cycles, greater terminal severity and much more severe yield losses. Changes in maximum or minimum temperature, even to the extent of 1 °C, will make all the difference between moderate and severe terminal disease development. Swarms of locusts produced in the Middle East usually fly eastward into Pakistan and India during the summer season and they lay eggs during the monsoon period. Changes in rainfall, temperature and wind speed pattern may influence the migratory behaviour of locusts.

Most crops have C_3 photosynthesis (responsive to CO_2) and many weeds are C_4 plants (non-responsive to CO_2). Climate change characterized by higher CO_2 concentration will favour crop growth over weeds, although temperature increase may further accelerate crop–weed competition, depending upon the threshold temperatures in different locations.

Socio-economic constraints

In addition to the biophysical determinants discussed above, the socio-economic environment, including government policies, capital availability, prices and returns, infrastructure, land reforms and inter- and intranational trade, is also an equally important determinant of crop production and hence food supply. Global environmental changes may alter the interactions between biophysical and socio-economic factors and the ways in which these are mediated by the institutions. Some recent studies have linked the biophysical response of crops, costs–benefits and the expected response of farmers to understand the socio-economic impact of global change. In the USA, maize production losses due to extremes of climate may double during the next 30 years, causing estimated additional damages of US$3 billion per year (Rosenzweig *et al.*, 2002). Developing countries are thought to be more vulnerable to extremes of climatic variability owing to their limited institutional and adaptation capacity.

Simulation studies involving biophysical and socio-economic modelling indicate that climate change is likely to increase the number of people at risk of hunger, depending on projected socio-economic developments. Fischer *et al.* (2002a) estimate that climate change will increase the number of undernourished people in 2080 by 5–26%. Parry *et al.* (2004, 2005), however, project small reductions by 2080, depending upon the climate change scenario. These studies also indicate that in future sub-Saharan Africa is likely to become the most food-insecure region of the world, and by 2080 may account for 40–50% of all undernourished people (Fischer *et al.*, 2002a; Parry *et al.*, 2004).

Conclusions

Changes in food demands, markets and agricultural technologies have led to major changes in the structure and function of agricultural ecosystems around the world. The pace of these changes is expected to increase rapidly in the coming years, and the whole agricultural scenario may become quite different in the next 10 to 20 years. Global climatic changes and increasing climatic variability are likely to further exert pressure on agricultural systems and change the balance among the key determinants of crop growth and yield. Efforts to assess the impacts, adaptation measures and vulnerability to climate change in this changing world scenario need to be strengthened.

References

Aggarwal, P.K. (2003) Impact of climate change on Indian agriculture. *Journal of Plant Biology* 30, 189–198.

Aggarwal, P.K., Kalra, N., Bandyopadhyay, S.K. and Selvarajan, S. (1995) A systems approach to analyse production options for wheat in India. In: Bouma, J., Kuynehoven, A., Bouman, B.A.M., Lutyen, J.C. and Zandstra, H.G. (eds) *Eco-regional Approaches for Sustainable Land Use and Food Production*. Kluwer, the Netherlands, pp. 167–186.

Aggarwal, P.K., Talukdar, K.K. and Mall, R.K. (2000) Potential yields of rice–wheat system in the Indo-Gangetic plains of India. Rice–Wheat Consortium Paper Series 10. RWCIGP, CIMMYT, New Delhi, India.

Aggarwal, P.K., Joshi, P.K., Ingram, J.S. and Gupta, R.K. (2004) Adapting food systems of the Indo-Gangetic plains to global environmental change: key information needs to improve policy formulation. *Environmental Science & Policy* 7, 487–498.

Arnell, N.W. (2004) Climate change and global water resources. SRES emissions and socio-economic scenarios. *Global Environmental Change* 14, 31–52.

Bhalla, G.S., Hazell, P. and Err, J. (1999) Prospects for India's cereal supply and demand for 2020. Food, Agriculture and the Environment Discussion Paper 29. IFPRI, Washington, USA.

Bruinsma, J. (ed.) (2003) *World Agriculture: Towards 2015/2030. An FAO Perspective*. Earthscan, UK.

Carter, T.R. and Saarikko, R.A. (1996) Estimating regional crop potential in Finland under a changing climate. *Agricultural and Forest Meteorology* 79, 301–313.

Chakraborty, S. and Datta, S. (2003) How will plant pathogens adapt to host plant resistance at elevated CO_2 under a changing climate? *New Phytologist* 159, 733–742.

Cocu, N., Harrington, R., Rounsevell, A., Worner, S.P. and Hulle, M. (2005) Geographical location, climate and land use influences on the phenology and numbers of the aphid, *Myzus persicae*, in Europe. *Journal of Biogeography* 32, 615–632.

Dobhal, D.P., Gergan, J.T. and Thayyen, R.J. (2004) Recession and morphogeometrical changes of Dokriani glacier (1962–1995), Garhwal Himalaya, India. *Current Science* 86, 692–696.

Doll, P. (2002) Impact of climatic change and variability on irrigation water requirements: a global perspective. *Climatic Change* 54, 269–293.

Easterling, W.E., Hurd, B. and Smith, J. (2004) *Coping with Global Climate Change. The Role of Adaptation in the USA*. Pew Center on Global Climate Change, USA.

Easterling, W.E., Aggarwal, P.K., Batima, P., Brander, K.M., Erda, L., Howden, S.M., Kirilenko, A., Morton, J., Soussana, J.-F., Schmidhuber, J. and Tubiello, F.N. (2007) Food, fibre and forest products. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E. (eds) *Climate Change 2007*: *Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, pp. 273–313.

Eheart, J.W. and Tornil, D.W. (1999) Low-flow frequency exacerbation by irrigation withdrawals in the agricultural Midwest under various climate change scenarios. *Water Resources Research* 35, 2237–2246.

FAO (2006) *The State of Food Insecurity in the World*. FAO, Rome.

Fischer, G., Shah, M. and van Velthuizen, H. (2002a) *Climate Change and Agricultural Vulnerability*. IIASA Special Report commissioned by the UN for the World Summit on Sustainable Development, Johannesburg 2002. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Fischer, G., van Velthuizen, H., Shah, M. and Nachtergaele, F.O. (2002b) *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. Research Report RR-02–02. International Institute for Applied Systems Analysis, Laxenburg, Austria, and CD-Rom.

Fischer, G., Tubiello, F.N., van Velthuizen, H. and Wiberg, D. (2006) Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. *Technological Forecasting and Social Change* 74, 1083–1107.

Grace, P.R., Jain, M.C., Harrington, L. and Philip Robertson, G. (2003) The long-term sustainability of tropical and subtropical rice and wheat systems: an environmental perspective. In: *Improving the Productivity and Sustainability of Rice–Wheat Systems: Issues and Impacts*. ASA Special Publication 65. American Society of Agronomy, Madison, USA, pp. 27–43.

Horie, T. (1993) Predicting the effects of climatic variation and effect of CO_2 on rice yield in Japan. *Journal of Agricultural Meteorology* (Tokyo) 48, 567–574.

Hossain, M. (1995) Sustaining food security for fragile environments in Asia: achievements, challenges and indications for rice research. In: *Fragile Lives in Fragile Ecosystems*. International Rice Research Institute, Los Baños, The Philippines, pp. 3–25.

IPCC (2001) *Climate Change 2001*: *Impacts, Adaptation and Vulnerability*. Intergovernmental Panel on Climate Change, Report of the Working Group II. Cambridge University Press, Cambridge, UK.

IPCC (2007a) *Climate Change 2007. The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds), Cambridge University Press, Cambridge, UK.

IPCC (2007b) *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds), Cambridge University Press, Cambridge, UK.

Khush, G.S. (1995) Breaking the yield frontier of rice. *Geo Journal* 35, 329–332.

Kimball, B.A., Kobayashi, K. and Bindi, M. (2002) Responses of agricultural crops to free-air CO_2 enrichment. *Advances in Agronomy* 77, 293–368.

Kulkarni, A.V. and Bahuguna, I.M. (2002) Glacial retreat in the Baspa basin, Himalaya, monitored with 17 satellite stereo data (Correspondence). *Journal of Glaciology* 48 (160), 171–172.

Kumar, P. (1998) Food demand and supply projection for India. Agricultural Economics Policy Paper 98–01, Indian Agricultural Research Institute, New Delhi, India.

Long, S.P., Ainsworth, E.A., Leakey, A.D.B., Nosberger, J. and Ort, D.R. (2006) Food for thought: lower expected crop yield stimulation with rising CO_2 concentrations. *Science* 312, 1918–1921.

Nearing, M.A., Pruski, F.F. and O′ Neal, M.R. (2004) Expected climate change impacts on soil erosion rates: a review. *Journal of Soil Water Conservation* 59, 43–50.

Newman, J.E. (1980) Climate change impacts on the growing season of the North American corn belt. *Biometeorology* 7(2), 128–142 (Supplement to *International Journal of Biometeorology* 24 (December 1980)).

Nohara, D., Kitoh, A., Hosaka, M. and Oki, T. (2006) Impact of climate change on river discharge projected by multimodel ensemble. *Journal of Hydrometeorology* 7, 1076–1089.

OECD–FAO (2007) *OECD–FAO Agricultural Outlook 2007–2016*. OECD/FAO, Rome, Italy.

Parry, M.L., Rosenzweig, C., Iglesias, A., Livermore, M. and Fischer, G. (2004) Effects of climate change on global food production under SRES emissions and socio-economic scenarios. *Global Environmental Change* 14, 53–67.

Parry, M.L., Rosenzweig, C. and Livermore, M. (2005) Climate change, global food supply and risk of hunger. *Philosophical Transactions of Royal Society B* 360, 2125–2138.

Peng, S. and Khush, G.S. (2003) Four decades of breeding for varietal improvement of irrigated lowland rice in the International Rice Research Institute. *Plant Production Science* 6, 157–164.

Peng, S., Khush, G.S. and Cassman, K.G. (1994) Evaluation of a new plant ideotype for increased yield potential. In: Cassman, K.G. (ed.) *Breaking the Yield Barrier. Proceedings of a Workshop on Rice Yield Potential in Favorable Environments*. International Rice Research Institute, Los Baños, The Philippines, pp. 5–20.

Rosegrant, M.W., Sombilla, M. and Perez, N.D. (1995) Global food projections to 2020: implications for investment, food, agriculture and the environment. Discussion Paper No. 5. IFPRI, Washington, DC, USA.

Rosenzweig, C. and Parry, M.L. (1994) Potential impact of climate change on world food supply. *Nature* 367, 133–138.

Rosenzweig, C., Tubiello, F.N., Goldberg, R., Mills, E. and Bloomfield, J. (2002) Increased crop damage in the US from excess precipitation under climate change. *Global Environmental Change* 12, 197–202.

RWC–CIMMYT (2003) *Addressing Resource Conservation Issues in Rice–Wheat Systems of South Asia: a Resource Book*. Rice–Wheat Consortium for the Indo-Gangetic Plains – International Maize and Wheat Improvement Center, New Delhi, India.

Salinari, F., Giosue, S., Tubiello, F.N., Rettori, A., Rossi, V., Spanna, F., Rosenzweig, C. and Gullino, M.L. (2006) Downy mildew epidemics on grapevine under climate change. *Global Change Biology* 12, 1–9.

Van Ittersum, M.K. and Rabbinge, R. (1997) Concepts in production ecology for analysis and quantification of agricultural input–output combinations. *Field Crops Research* 52, 197–208.

Van Ittersum, M.K., Howden, S.M. and Asseng, S. (2003) Sensitivity of productivity and deep drainage of wheat cropping systems in a Mediterranean environment to changes in CO_2, temperature and precipitation. *Agriculture Ecosystems and Environment* 97, 255–273.

6 Yield Gap Analysis: Modelling of Achievable Yields at Farm Level

P. Singh,[1]* P.K. Aggarwal,[2] V.S. Bhatia,[3]*** M.V.R. Murty,[1]**** M. Pala,[4] T. Oweis,[4]***** B. Benli,[4] K.P.C. Rao[5]****** and S.P. Wani[1]*******

*[1]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India; [2]Indian Agricultural Research Institute (IARI), New Delhi 110 012, India; [3]National Research Centre for Soybean (NRCS), Khandwa Road, Indore 452 017, Madhya Pradesh, India; [4]International Center for Agricultural Research in the Dry Areas (ICARDA), PO Box 5466, Aleppo, Syria; [5]International Center for Research on Agroforestry (ICRAF), Nairobi, Kenya; emails: *p.singh@cgiar.org; **pramodag@vsnl.com; ***Bhatia_virender-singh@hotmail.com; ****murtymur@rediffmail.com; *****t.oweis@cgiar.org; ******k.p.c.rao@cgiar.org; *******s.wani@cgiar.org*

Introduction

The world population is expected to reach about 8 billion by 2025 (United Nations, 2006), before it stabilizes at about 10–11 billion towards the end of the 21st century. Most of this increase in population is expected to occur in less-developed countries, where most of the poor live and where rainfed agriculture forms the dominant basis for livelihood security. Asia and Africa will be the major contributors to this increase in population (Table 6.1). More food will be needed in future in view of expected increases in population, the extent to which malnutrition is to be overcome and the changing food habits of people towards more animal-based foods. Many countries in Asia and Africa will have to import more food to meet their food requirements in future (Table 6.1). At least in the foreseeable future, plants, especially the cereals, will continue to supply much of our increased food demand, both for human consumption and as feed for livestock to satisfy the rapidly growing demand for meat, milk and eggs in the newly industrialized countries. It is estimated that an additional 1 billion t of grain will be needed annually by 2025. Most of this increase must be supplied from lands already in production, through yield improvements (Borlaug, 2001).

Much of the past progress in boosting agricultural productivity has taken place in more favourable irrigated areas. Prospects of further irrigation developments are limited in Asia, and despite high development potential in sub-Saharan Africa (SSA), the last decades have shown a decline in irrigation expansion. In the last few decades the emerging evidence indicates that crop productivity growth in irrigated areas has slowed or stagnated due to multiple factors. As sources of growth in irrigated areas decline, rainfed agriculture must increase to fill the gap. Because of population increase and competing demands for land for other sectors of the economy, especially in the South Asian region, most of the increase in food production will have to take place from increase in productivity per unit of land rather than area increase under agriculture.

Rainfed Agriculture: Unlocking the Potential
(eds S.P. Wani *et al.*)

Table 6.1. Current and expected population increase, food demand and net import in the selected regions of the world[a].

Region	Current population (million)	Expected population in 2025 (million)	Food demand in 1995 (million t)	Expected food demand in 2025 (million t)	Net import in 1995 (million t)	Expected net import in 2025 (million t)
South-east Asia	558	686	113.5	176	7	6.2
South Asia	1646	2146	226.2	376.3	0.2	40.1
Sub-Saharan Africa	769	1194	78.4	172.4	9.8	34.9
West Asia and North Africa	402	548	120.2	202	37.8	83
World	6671	8011	1778.6	2606.4	–	–

[a] Source: Rosegrant *et al.* (2002); United Nations (2006).

The semi-arid regions of Asia and Africa are primarily dependent on rainfed agriculture, where the agricultural productivity of rainfed systems is low. Sub-Saharan Africa and South Asia will remain 'hot spots' of child malnutrition, food insecurity and poverty, where underdevelopment, rapid population increase, land degradation, climate uncertainty and water scarcity, and unfavourable government policies are the major bottlenecks to achieving higher agricultural production and improved rural livelihoods. Future climate change due to global warming will have a negative effect on crop yields, thus making the matter worse in achieving the Millennium Development Goals of food security in the developing world.

While the food production increases in future must occur in the rainfed areas of Asia and Africa, it is also important to know where, how and how much additional food can be produced in different regions to meet the increasing food demand. Estimates of the potential production of regions can assist in quantifying carrying capacity of agroecosystems. The purpose of this chapter is to quantify the potential yields and yield gaps between the potential and the actual yields obtained by the farmers for the major rainfed crops grown in the selected countries in South and South-east Asia (India, Thailand and Vietnam), SSA and the West Asia and North Africa (WANA) region, where food security in future is increasingly threatened because of expected increase in population and degradation of natural resources. This analysis will help identify the opportunities and constraints for yield improvement in future with the implementation of the improved crop production and natural resource management technologies for the rainfed regions.

Data and methods adopted to quantify potential yields and yield gap of crops varied across countries, depending upon the nature of data availability to perform such analyses. Broadly, the potential yields and yield gaps of the crops were estimated based upon the data generated through crop simulation methods, research station yield maximization trials, on-farm technology demonstrations with improved management, and farmers' actual yields reported at state, district or province level by each country.

Yield Gap Analysis of Crops in South and South-east Asia

Yield gap analysis of rainfed crops in India

By 2025, India's population is expected to reach 1.45 billion from the current level of 1.17 billion (United Nations, 2006). The cereal requirement of India by 2020 will be between 257 and 296 million t, depending on income growth (Kumar, 1998; Bhalla *et al.*, 1999). It is necessary that food production in India must increase by about 5 million t annually for the next 25 years to ensure food and nutritional security to the burgeoning population (Kanwar, 2000). Irrigated green revolution areas are already showing signs of fatigue due to further increase in crop production. It is believed that rainfed areas, which cover almost 70% of the total land area under agriculture in India, would have a greater share in meeting the future food needs of the country due to increasing population (Kanwar, 2000; Singh *et al.*, 2000). By 2020, about 600 million people would be living in rainfed regions besides an estimated 650 million head of livestock. The current level of productivity of rainfed cereals ranges from 520 to 1320 kg/ha and that of pulses from 540 to 650 kg/ha, which is quite low compared with what can be potentially achieved. The per capita land availability in rainfed areas is expected to fall from 0.28 ha in 1990 to 0.12 ha by 2020 (Singh *et al.*, 2000). It means more food has to be produced from each unit of land to meet the growing food needs in future.

Biophysical environment and production systems of the rainfed areas

The rainfed areas are spread out widely in the country from north to south and east to west. They can be broadly classified into arid, semi-arid (dry), semi-arid (wet) and dry subhumid agroecologies (Fig. 6.1 and Table 6.2). These agroecologies vary substantially in their production potential, cropping systems being followed by the farmers and the constraints limiting production. There are six major soil orders that dominate the rainfed areas of India (Fig. 6.1 and Table 6.2). The soils of the semi-arid tropics (SAT) are poor in fertility, low in organic matter, prone to severe degradation, undulating in physiography and shallow in depth. Vegetative cover is sparse due to the extended period of aridity and over-exploitation for crop production and grazing. Lack of surface cover promotes erosion due to run-off water and wind (Wani *et al.*, 2003a). Most dryland soils are deficient in nitrogen and phosphorus. Vertisols developed on granite and sedimentary rocks are more deficient in phosphorus than those on basalt (Singh and Venkateswarlu, 1985). In the SAT, the deficiency of potassium was noticed in certain coarse-textured soils, some red soils and in soils on which high crop yields were obtained without potassium application for a long period (Venkateswarlu, 1987). In addition to the three critical elements, widespread deficiency of sulfur, zinc, boron and iron have also been reported (Rego *et al.*, 2007). The opportunities for water harvesting increase from arid agroecology to dry subhumid agroecology with an increase in amount of rainfall. Rainfed agriculture in these agroecologies is rarely practised as a single crop or livestock system. Mixed farming and diversity are the main features. The major crop production systems of rainfed agriculture are rainfed rice and wheat, coarse cereals (sorghum, pearl millet and maize), pulses (pigeonpea and chickpea), oilseeds (soybean, groundnut, sunflower, rape seed and mustard) and cotton. These crops have a significant role in the economy of a given area in view of the area and production.

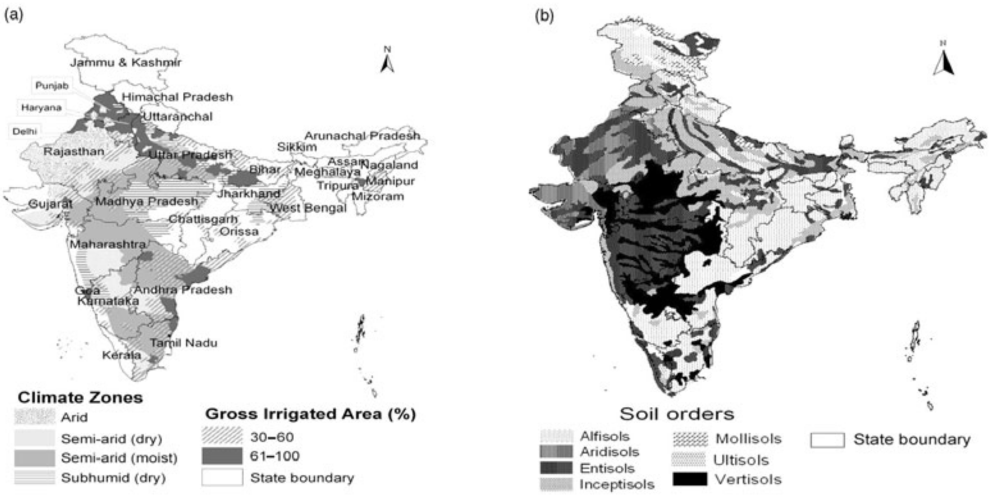


Fig. 6.1. (a) Climate zones and states and (b) soils of India.

Table 6.2. Biophysical characteristics and dominant production systems of various rainfed agroecologies of India[a].

Attributes	Agroecology			
	Arid	Semi-arid dry	Semi-arid wet	Subhumid dry
% of geographical area	19.6	12	25.9	21.1
Rainfall (mm)	<500	501–700	701–1100	1101–1600
Soils	Aridisols, vertic-vertisols	Vertisols, vertic inceptisols, alfisols	Vertic inceptisols, alfisols, entisols	Vertisols, vertic soils, alfisols, mollisols, entisols
Length of growing period (days)	60–90	90–120	120–150	150–210
Production systems	Pearl millet, short-duration pulses, perennials and livestock farming	Pearl millet, groundnut, *kharif* and *rabi* sorghum and cotton-based systems	Soybean-based, maize-based and sorghum-based systems	Rainfed rice followed by pulses and oilseeds

[a] Source: Singh *et al.* (2000).

Methods of yield gap analysis

The potential yields were estimated using a crop simulation approach and review of research station experimental data. The yields estimated coupled with the state-level yields were used to estimate the yield gaps for a particular crop as described below.

SIMULATED RAINFED POTENTIAL YIELDS This is the potential yield of an improved variety simulated by the crop growth model under optimal management conditions, except that water availability is the main limiting factor for crop growth. We used Decision Support System for Agrotechnology Transfer (DSSAT) v3.5 software (Hoogenboom *et al.*, 1999) to simulate potential yields of sorghum, pearl millet, maize, soybean, groundnut and chickpea; InfoCrop software (Aggarwal *et al.*, 2006) for rice and cotton, and APSIM software (McCowen *et al.*, 1995) for pigeonpea. All the crop models in these software need similar kind of weather (daily solar radiation, maximum and minimum temperatures and rainfall) data, soil profile data and cultivar-specific parameters (genetic-coefficients) to simulate crop growth, yield and resource use by the crops. Multi-year simulation of the rainfed potential yield of a crop was carried out for several locations in a state and averaged over time and space to estimate the rainfed potential yields. These have been described in detail for legumes by Bhatia *et al.* (2006) using DSSAT. A similar method was followed for other crops using APSIM or InfoCrop software.

EXPERIMENTAL STATION YIELDS This is the maximum possible rainfed yield of an improved cultivar usually obtained at the experimental stations in research plots under good care and supervision when factors other than water availability have minimal effect on limiting crop growth. To obtain these yields, the annual reports of the All India Coordinated Research Projects (AICRPs) of various crops since the late 1990s were reviewed. The yields obtained for the top five entries of legumes (soybean, groundnut, chickpea and pigeonpea) and of all the entries of cereals (sorghum, pearl millet and maize) were averaged for each year and location to calculate the rainfed yield potential. These were further averaged over the years and compared with the state/district level average yields for estimating yield gap.

STATE MEAN YIELDS State mean yields were determined from the area and production data of a crop for each district in a state. Total production was divided by the total area under the crop in a state to calculate state mean yield. Mean yields were then further averaged over the years (number of years depending upon the data availability) and compared with the potential yields to estimate yield gaps.

YIELD GAPS Yield gaps were quantified using simulated potential yields, experimental potential yields and the state mean yields, all obtained under rainfed conditions. Simulated yield gap was the difference between the simulated mean potential yield and the mean state yield. The experiment station yield gap was calculated as the difference between the experiment station mean yield and the mean state yield.

Potential yield and yield gap of cereals

RICE Rice in India is grown almost throughout the country except for the arid eastern parts of Rajasthan. Of the 43 million ha of harvested rice area, almost 51% is now irrigated. Most of the rice-producing areas of Punjab, Haryana, Andhra Pradesh and Tamil Nadu are irrigated. Rainfed rice is grown in several states, such as West Bengal, Uttar Pradesh, Orissa, Bihar, Assam, Karnataka, Maharashtra, Madhya Pradesh and Jharkhand. The production of rice in India has increased from 42.7 million t during 1972–1976 to 85.3 million t during 2002–2006 (Table 6.3). This has been due to an increase in the area under rice in the initial years and later due to an increase in yield per ha and irrigation coverage.

Today, West Bengal, Uttar Pradesh, Andhra Pradesh, Punjab and Orissa alone account for 60% of the total rice production and almost 50% of the total rice area of India. The mean yield of rice is more than 3000 kg/ha in several districts of Punjab, Haryana, Andhra Pradesh and Tamil Nadu. Farmers in these states have much higher per capita income than do the traditional rice-growing states of eastern India. The yields are generally less than 2000 kg/ha in central Indian rainfed states such as Madhya Pradesh and in eastern Indian states such as Orissa and Bihar (Fig. 6.2), where the production is strongly associated with the distribution of rainfall. In some eastern states, erratic rainfall leads to drought during the vegetative period, but later on the crop may be damaged by submergence due to high rainfall. Other constraints relate to the land and soil, such as soil acidity in southern and eastern India, salinity and alkalinity in northern India.

Table 6.3. Area, production and yield of cereals from 1972–1976 to 2002–2006 in India[a].

Attribute	1972–1976	1982–1986	1992–1996	2002–2006
Rainfed rice				
Area (million ha)	38.2	40.6	42.7	43
Production (million t)	42.7	58.0	78.7	85.3
Yield (kg/ha)	1120	1430	1840	2000
% irrigated area	39	43	49	50
Maize				
Area (million ha)	6.0	5.8	6.1	7.4
Production (million t)	6.3	7.4	9.8	13.8
Yield (kg/ha)	1050	1280	1630	1870
% irrigated area	17.7	19.2	21.5	19.3
Kharif sorghum				
Area (million ha)	10.3	10.1	6.4	4.1
Production (million t)	6.6	7.7	7.2	4.1
Yield (kg/ha)	640	760	1130	1000
Rabi sorghum				
Area (million ha)	5.8	6.1	5.6	4.9
Production (million t)	2.7	3.0	3.5	3.3
Yield (kg/ha)	460	490	640	640
Pearl millet				
Area (million ha)	11.9	11.1	9.9	9.3
Production (million t)	5.3	5.4	6.9	8.1
Yield (kg/ha)	440	490	680	870

[a] Source: GOI (2006).

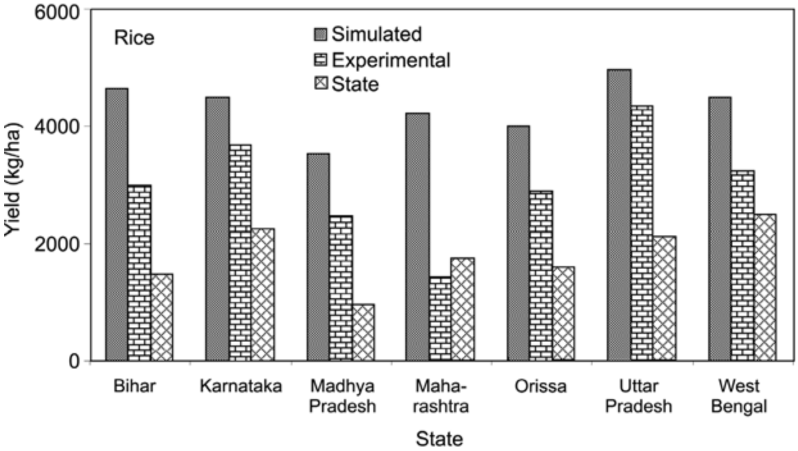


Fig. 6.2. Mean simulated potential, experimental and measured state-level yields of rice in India. Note that measured yields are average values of irrigated and rainfed areas.

The simulated rice yields varied considerably across major rainfed states, depending upon rainfall, soil and other location-specific factors. The mean rainfed simulated potential yield varied from 3540 kg/ha in Madhya Pradesh to 4970 kg/ha in Uttar Pradesh (Fig. 6.2). The experimental potential yields showed a large variation from 1420 kg/ha in states such as Maharashtra to 4350 kg/ha in Uttar Pradesh. The farmers' mean yields at the state level showed considerable variation (Fig. 6.2). These were lowest in Madhya Pradesh followed by Bihar and Orissa. By comparison, the mean yields in Karnataka, Uttar Pradesh and West Bengal were more than 2000 kg/ha. It is difficult to draw any meaningful conclusion from such state mean yields because a considerable fraction of these were from irrigated areas. Nevertheless, rainfed yields in these states will be lower still than the values presented here.

The results showed that, irrespective of the definition of potential yield, there is a considerable yield gap across all states, indicating a large scope for increasing rainfed rice yields in future. On average, the gap relative to simulated potential was close to 2500 kg/ha. It was more than 3000 kg/ha for Bihar and less than 2000 kg/ha for West Bengal. At the experimental station level, the gap varied from 740 kg/ha (in West Bengal) to 2230 kg/ha (in Uttar Pradesh). This value was around 1500 kg/ha in all other states.

MAIZE Maize is the third most important crop in terms of total production among cereals in India. The five major states producing maize in the country are Madhya Pradesh, Bihar, Karnataka, Uttar Pradesh, Rajasthan and Andhra Pradesh. Most of the maize (about 90%) in India is grown during the summer monsoon season (*kharif*) under rainfed condition. It currently occupies 7.4 million ha with production of 13.8 million t with an average productivity of about 1870 kg/ha (Table 6.3). The increase in production of maize over the years in India has been because of increase in both area and yield of the crop. Maize cultivation in most of the states is under moderate input supply conditions due to various biophysical and socio-economic drivers which have held back the maize yield. Thus, there is greater scope to increase its productivity from the current levels.

The maize yields were simulated for Madhya Pradesh (Guna and Indore), Bihar (Patna), Uttaranchal (Pantnagar), Uttar Pradesh (Varanasi), Rajasthan (Kota) and Andhra Pradesh (Hyderabad). The simulated yields for most of the states were higher than the experimental yields and ranged from 4320 to 6630 kg/ha across states (Fig. 6.3). The experimental yields ranged from 3160 to 4640 kg/ha across states. These yields were almost double the actual state-level yields, which ranged from 1090 to 2460 kg/ha across states. The yield gap

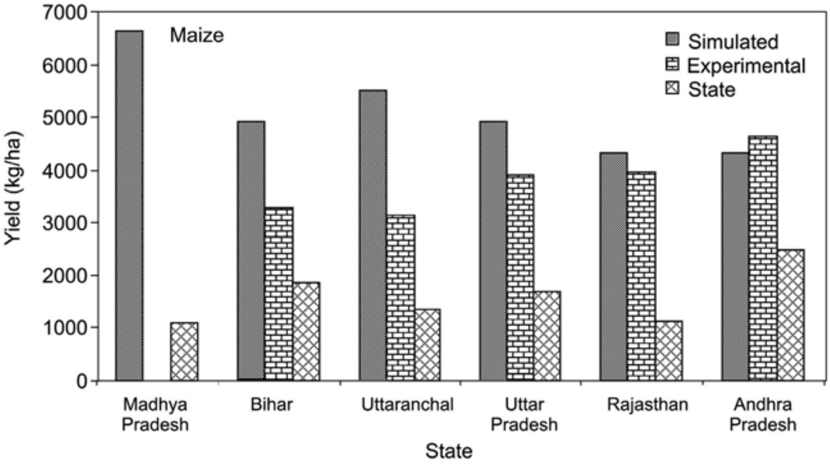


Fig. 6.3. Mean simulated, experimental and measured state-level yields of maize in India.

based on the mean simulated yields ranged from 1860 to 5540 kg/ha across states; the highest yield gap was for Madhya Pradesh and the lowest for Andhra Pradesh. Based upon the experimental yield, the yield gap across locations ranged from 1430 to 2840 kg/ha across states. These results show that the farmers' yields under rainfed situations can be more than doubled in the states through proper agronomic management involving improved varieties and soil fertility management.

SORGHUM Sorghum is grown in India during both the rainy (*kharif*) and post-rainy (*rabi*) seasons. It is an important source of food for people and fodder for livestock in the rainfed regions of India. The total area under *kharif* sorghum has declined from 10.3 million ha during 1972–1976 to 4.1 million ha during 2002–2006 (Table 6.3). Similarly, total production declined from 6.6 million t to 4.1 million t after some increase during the early 1980s and 1990s. However, the yield per ha increased from 640 to 1000 kg/ha. Maharashtra is the largest *kharif* sorghum growing state with about 1.8 million ha out of the total 4.1 million ha grown in India. Madhya Pradesh and Rajasthan come next with 0.61 million ha each, followed by Karnataka with 0.34 million ha. Maharashtra produces 2.3 million t out of a total production of 4.10 million t of sorghum produced in the country. Uttar Pradesh, Andhra Pradesh, Tamil Nadu and Gujarat are the other states having a large area under sorghum.

Kharif sorghum. The mean simulated rainfed potential yield in Karnataka was the highest (3640 kg/ha), followed by Madhya Pradesh (3610 kg/ha) and Maharashtra (3220 kg/ha). The experimental station yields ranged from 2280 to 4580 kg/ha, the highest being for Karnataka and the lowest for Uttar Pradesh. Based on the simulated yields, the yield gap ranged from 1940 to 2750 kg/ha. However, based on the experiment station yields, the yield gaps were low and ranged from 1340 to 3280 kg/ha across states (Fig. 6.4). These results on yield gap indicate the potential to enhance productivity of *kharif* sorghum in different states by adopting improved agronomic management practices of sorghum production.

Rabi sorghum. Mean experimental potential yields for the three major states ranged from 1940 to 2960 kg/ha, the highest being for Andhra Pradesh and the lowest for Maharashtra (Fig. 6.5). The simulated potential yields were lower than the experimental station yields, which were 1110 kg/ha for Maharashtra and 1640 kg/ha for Karnataka. This is because rainfed simulations were carried out for a longer period, often for 15–26 years for each location, than the number of years for which the experimental data were available. Thus, the simulations captured

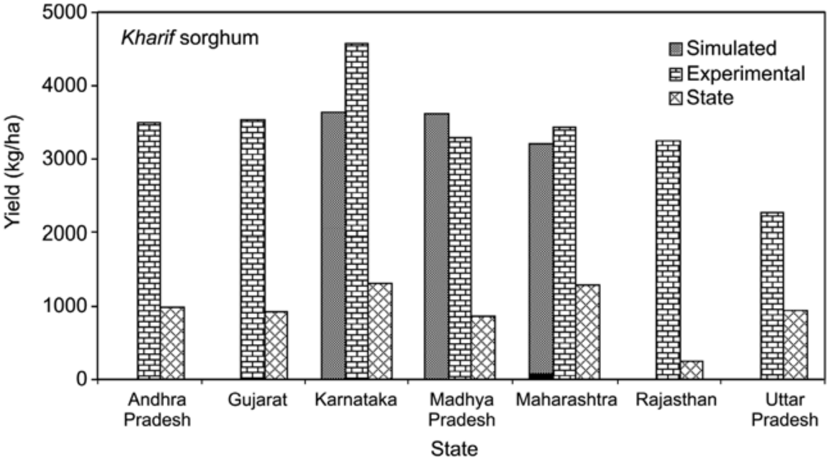


Fig. 6.4. Mean simulated, experimental and measured state-level yields of *kharif* sorghum in India.

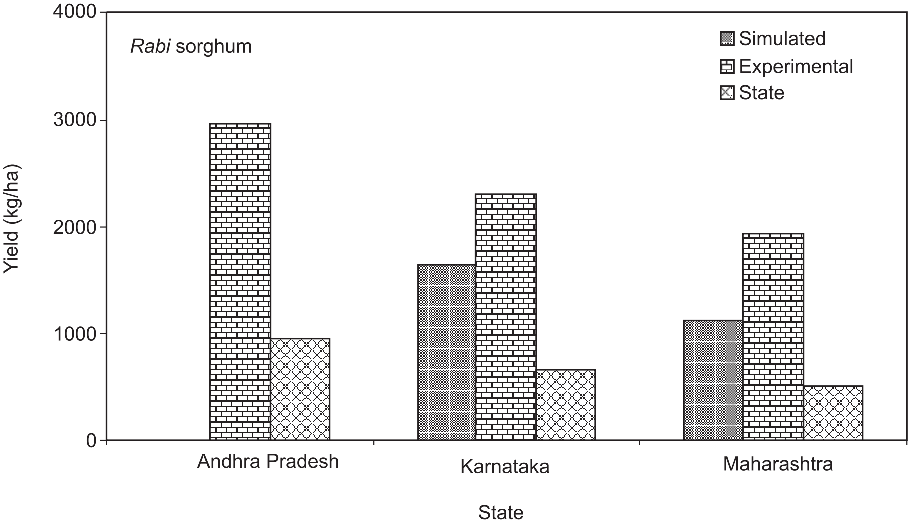


Fig. 6.5. Mean simulated, experimental and measured state-level yields of *rabi* sorghum in India.

more effects of temporal and spatial variations in rainfall on crop yields than the experimental yields. Based upon the experimental yields, the yield gap ranged from 1430 to 2020 kg/ha for the three states. However, the yield gap between the simulated potential yield and the state yield was 600 kg/ha for Maharashtra and 990 kg/ha for Karnataka. These results indicate that *rabi* sorghum yields in the three states can at least be doubled with improved crop management practices comprising improved variety, nutrient management and timely sowing of the crop immediately after the cessation of monsoon rains. Supplemental irrigation to the crop would further enhance the crop yields.

Total area of *rabi* sorghum in the country has decreased from 5.8 million ha in 1972–1976 to 4.9 million ha in 2002–2006; however, total production has increased from 2.7 million t to 3.3 million t during the same period (Table 6.3). This was possible due to an increase in yield from 460 kg/ha to 640 kg/ha during the span of 30 years. Maharashtra has the largest area (3.21 million ha) under *rabi* sorghum followed by Karnataka (1.45

million ha) and Andhra Pradesh (0.35 million ha).

Unfavourable soil physical conditions preventing advanced sowing and low water-holding capacity of shallow black soils, leading to terminal drought to the crop, are the main reasons preventing the significant increase in productivity of *rabi* sorghum in a sustainable manner. Therefore, the input components, including supplemental irrigation, rather than the high-yielding varieties of *rabi* sorghum, were responsible for the increase in productivity.

PEARL MILLET The total area under pearl millet decreased from about 11.9 million ha during 1972–1976 to about 9.3 million ha during 2002–2006 (Table 6.3). Total production increased from 5.3 million t during 1972–1976 to 8.1 million t during 2002–2006. This increase in production was because of an increase in yield from 440 kg/ha to 870 kg/ha during the same period. Rajasthan has the highest area (4.74 million ha) under pearl millet production. Other states cover about 0.61 million ha under pearl millet. The average yields across states range from 670 to 1280 kg/ha.

Mean simulated rainfed yield of Rajasthan was the lowest at 1460 kg/ha, whereas Madhya Pradesh had the highest mean yields of 2530 kg/ha. Karnataka and Maharashtra had a simulated mean yield of 2170 kg/ha and 2000 kg/ha, respectively (Fig. 6.6). The potential yields for Andhra Pradesh, Gujarat, Haryana and Tamil Nadu could not be simulated because of the lack of input data for executing the pearl millet model. The experimental potential yields were the lowest at 1440 kg/ha for Rajasthan and the highest at 3550 kg/ha for Tamil Nadu. The yield gap between simulated mean yield and state-level mean yield ranged from 670 to 1660 kg/ha, the lowest being for Rajasthan. Yield gaps based on experimental data were low for Rajasthan, Haryana and Gujarat and ranged from 610 to 920 kg/ha, whereas for other states, the yield gaps ranged from 1260 to 2480 kg/ha and the highest was for Tamil Nadu. These results show that, except for Gujarat, Haryana and Rajasthan, the farmers' yield can be more than doubled with improved crop production technology including improved varieties and nutrient management.

Potential yield and yield gap of pulses

India is the largest producer of pulses in the world. They are important for protein production, nitrogen-fixing ability and adaptability to cropping systems. Among these, pigeonpea and chickpea are the most important ones. Often these form part of the intercropping, sequence cropping or traditional mixed seeding systems,

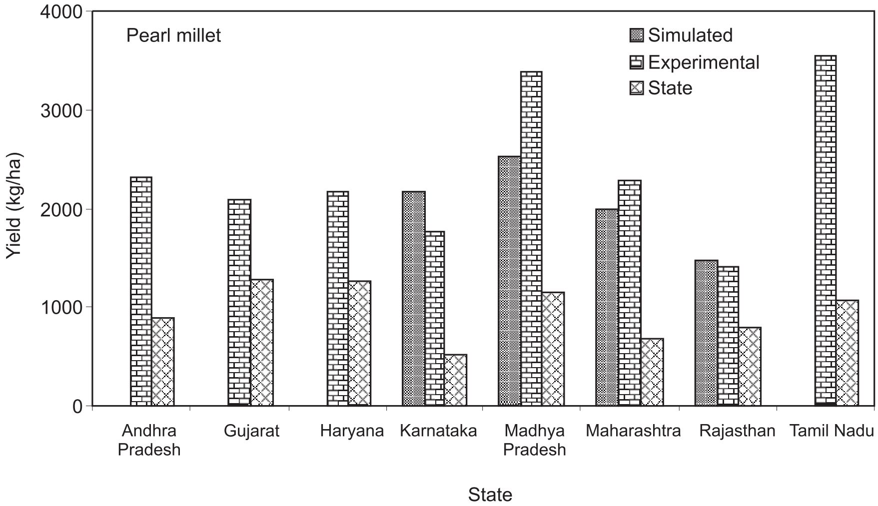


Fig. 6.6. Mean simulated, experimental and measured state-level yields of pearl millet in India.

providing the much-needed stability to the production system. Pigeonpea, particularly owing to its long duration, is often intercropped with short-duration cereals, so that the land equivalent ratio is optimized. Over 90% of pigeonpea, mainly long-duration and medium-duration cultivars, is grown in dryland areas as a mixed crop or intercropped with cereals (sorghum, maize, pearl millet), legumes (groundnut, soybean, black gram, green gram, cowpea) and commercial crops (cotton, castor, cassava) (Singh *et al.*, 2000). However, more recently short-duration pigeonpea is being grown as a sole crop during the rainy season in some areas in north India as part of the crop rotation in the rice–wheat production system.

PIGEONPEA Over the years, the area under pigeonpea in India has increased from about 2.6 million ha during 1972–1976 to 3.5 million ha during 2002–2006 (Table 6.4). However, during the corresponding years, the total production has been fluctuating and ranged from 1.8 million t in 1972–1976 to 2.4 million t during 2002–2006. This increase in production was primarily because of an increase in the area under pigeonpea rather than an increase in productivity. Among the states, Maharashtra has the largest area (1.03 million ha), which accounts for 31% of the total pigeonpea area in the country. The other five states, namely Uttar Pradesh, Karnataka, Gujarat, Madhya Pradesh and Andhra Pradesh, each having an area of about 10–12%, together contribute 60% of the total pigeonpea area in the country.

Average simulated potential yields across the states ranged from 830 to 1960 kg/ha, the lowest being for Gujarat and the highest for Uttar Pradesh (Fig. 6.7). The experimental station mean yields across states ranged from 1370 to 1840 kg/ha, which were somewhat higher than the mean simulated yields for most of the states. Among the states, the average state-level productivity was the highest for Uttar Pradesh (1090 kg/ha), followed by Gujarat (880 kg/ha) and Madhya Pradesh (810 kg/ha). The average productivity was less than the national average (690 kg/ha) in Maharashtra (610 kg/ha), Karnataka (410 kg/ha) and Andhra Pradesh (330 kg/ha). Both the simulated and the experimental station yields indicated that in major pigeonpea-growing regions in India, the average rainfed

Table 6.4. Area, production and yield of legumes (pulses and oilseeds) and cotton from 1972–1976 to 2002–2006 in India[a].

Attribute	1972–1976	1982–1986	1992–1996	2002–2006
Pigeonpea				
Area (million ha)	2.6	3.1	3.5	3.5
Production (million t)	1.8	2.4	2.4	2.4
Yield (kg/ha)	700	760	700	690
Chickpea				
Area (million ha)	7.6	7.3	6.9	6.8
Production (million t)	4.8	5.0	5.3	5.4
Yield (kg/ha)	630	690	770	790
Soybean				
Area (million ha)	0.1	1.1	4.6	7.2
Production (million t)	0.1	0.8	4.5	7.3
Yield (kg/ha)	880	700	980	1000
Groundnut				
Area (million ha)	7.1	7.2	7.9	6.2
Production (million t)	5.4	6.0	8.1	6.4
Yield (kg/ha)	770	830	1030	1020
Cotton				
Area (million ha)	7.4	7.5	8.2	8.4
Production (million t)	6.2	7.6	12.2	15.7
Yield (kg/ha)	140	170	250	310

[a] Source: GOI (2006).

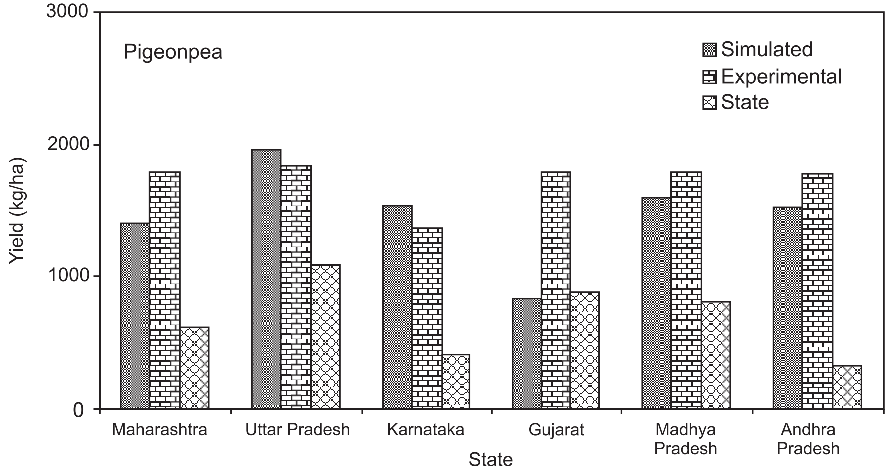


Fig. 6.7. Mean simulated, experimental and measured state-level yields of pigeonpea in India.

potential is almost double as compared with the national average (690 kg/ha) and indicates that there are ample opportunities for improving the production and productivity of the pigeonpea crop in India.

CHICKPEA India is the largest producer of chickpea in the world. It accounts for 61% of the total area and 66% of total production in the world. In India chickpea represents 32% (6.8 million ha) of the total pulses area and 49% (5.4 million t) of the total pulses production. During 1972–1976, chickpea was cultivated in 7.6 million ha with a production of 4.8 million t. After 1972–1976, the area under chickpea gradually decreased, whereas the average production showed a slight increase (Table 6.4). During 2002–2006, the area and production of chickpea was 6.8 million ha and 5.4 million t, respectively. The productivity of the crop has been fluctuating greatly and has shown an increase from 630 kg/ha in 1970 to 790 kg/ha during the same period. Being a *rabi* crop, chickpea fits very well in the sequence cropping systems in north and central India (Singh *et al.*, 2000).

With an area of about 2.6 million ha and production of 2.4 million t, Madhya Pradesh alone contributes 37% of the total area and 42% of the total production of chickpea in the country. The soybean–chickpea cropping system has become a well-established and profitable cropping system in the rainfed area of this state. Other major chickpea-producing states are Rajasthan (1.08 million ha), Maharashtra (1.02 million ha), Uttar Pradesh (0.74 million ha), Karnataka (0.42 million ha) and Andhra Pradesh (0.39 million ha). Average yield in these states ranges from 550 to 1590 kg/ha, with Andhra Pradesh having the highest yield (GOI, 2006).

Across the chickpea-growing states, the average potential yield of chickpea ranged from 1250 to 2120 kg/ha. The major rainfed area under chickpea in India is spread across Madhya Pradesh, Maharashtra and Karnataka. The average simulated yields in these states were 1620, 1860 and 2120 kg/ha, respectively. The average experimental station yields for these states were 2060, 1460 and 1350 kg/ha, respectively (Fig. 6.8). Average state-level productivity of Madhya Pradesh, Maharashtra and Karnataka is 880, 560 and 460 kg/ha, respectively. Rajasthan and Uttar Pradesh, where the crop is grown with supplemental irrigation, have productivity levels of 830 and 870 kg/ha, respectively. In general, it is evident from the simulated as well as the experimental station yields that the potential of rainfed chickpea in the major geographical regions is between 1250 and 2200 kg/ha, which is substantially higher than the present national average of about 800 kg/ha. Chickpea yield

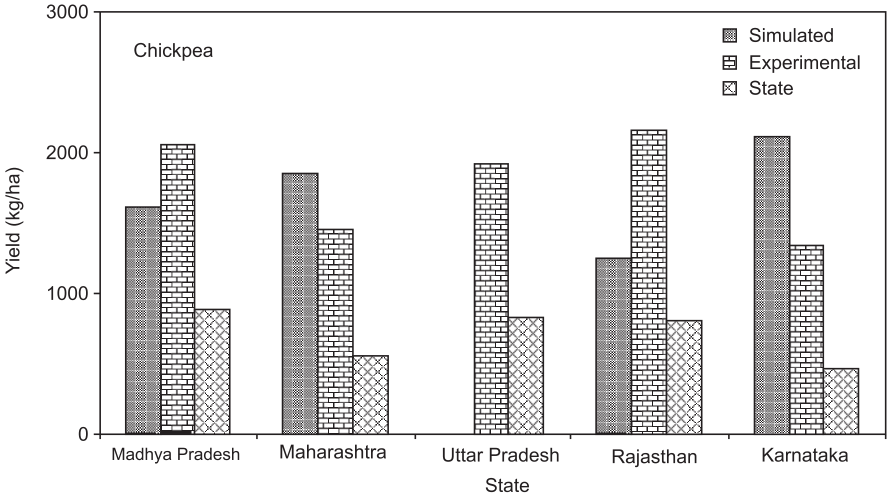


Fig. 6.8. Mean simulated, experimental and measured state-level yields of chickpea in India.

gaps can be bridged by adoption of high-yielding varieties and improved agronomic management. Supplemental irrigation will be an essential component of technologies to increase productivity of chickpea in India.

Potential yield and yield gap of oilseeds

India occupies a premier position with regard to oilseed production, covering 19% of the area and 10% of the production in the world (Singh *et al.*, 2000). All the oilseed crops together are grown on an area of 25.3 million ha, which is next only to food grains. The multiplicity of crops and growing environments makes India's oilseed production scenario a complex one. By and large, the production always lags behind the requirement. Groundnut, rapeseed, mustard, sunflower, safflower, soybean, sesame and castor are the important oilseed crops. Most of these crops are grown under rainfed conditions and on poor soils constrained with water and nutrient stresses. The production and productivity of these oilseeds have remained more or less stagnant but for a modest gain in selected crops following the launching of the technology mission on oilseeds (Singh *et al.*, 2000). Considering their importance in terms of area and production, only soybean and groundnut are dealt with in these yield gap studies.

SOYBEAN In India, soybean has shown a spectacular growth in production, which increased from 0.1 million t in 1972–1976 to 7.3 million t in 2002–2006. This was primarily due to an increase in the area under soybean with moderate yield enhancement from 880 kg/ha to 1000 kg/ha during the same period (Table 6.4). The soybean crop is primarily cultivated in three states, namely Madhya Pradesh, Maharashtra and Rajasthan, which contribute 98 and 99% of the total soybean area and production of the country, respectively. However, among these three states Madhya Pradesh, with 4.23 million ha area and 4.29 million t of production, is the dominant state with a net 71 and 74% contribution to total soybean area and production in the country.

Two major soybean-growing states in the country (Madhya Pradesh and Maharashtra) have a rainfed yield potential of more than 2000 kg/ha, which is more than double as compared with the existing national productivity of less than 1000 kg/ha. The potential yield was found to be marginally low in Karnataka (1750 kg/ha), while Rajasthan, for which the weather data were available for only one predominant location (Kota), showed a very low simulated potential rainfed yield of 1340 kg/ha. The experimental station yields were also above 2000 kg/ha and ranged from 2080 to 2600 kg/ha. Significantly, low simulated soybean yields as compared with the experimental yields in Rajasthan and Karnataka are because of long-term effects of climatic variability considered during simulation, which was not possible with the experimental data. The state-level mean yields ranged from 640 to 1210 kg/ha (Fig. 6.9). The comparison of potential yields with actual state yields show that, except for Rajasthan, the soybean yields can be almost doubled by adoption of improved agronomic practices.

GROUNDNUT In India, groundnut is the major oilseed crop. The total area under groundnut production during the period 1972–1976 was 7.1 million ha, which increased to 7.9 million ha during 1992–1996 and thereafter declined to 6.2 million ha during 2002–2006 (Table 6.4). A similar trend as for area was observed in total production of groundnut during the period from 1972–1976 to 2002–2006. The total increase in production until 1992–1996 was due to increase in both area and yield, which increased from 770 kg/ha during 1972–1976 to 1030 kg/ha during 1992–1996. After 1992–1996, the yield levels of groundnut stagnated at about 1020–1030 kg/ha. The sharp rise in area and production of groundnut in the post-1987 period was mainly due to the major efforts of the government under the technology mission for groundnut production, which could not be sustained. Groundnut production declined after achieving a peak production of 9.68 million t in 1988–1989.

Among the states, Andhra Pradesh and Gujarat together contribute 52% to the total groundnut area and production in the country. Another 34% is contributed by Karnataka, Tamil Nadu and Maharashtra. The rest of the area is scattered in the states of Rajasthan, Orissa, Madhya Pradesh and other parts of India.

Among the major states covering the groundnut area in India, the simulated potential rainfed yield was more than 2000 kg/ha (2330–3490 kg/ha) except for Tamil Nadu (1200 kg/ha) (Fig. 6.10). The experimental yields for the states ranged from 1660 to 2590 kg/ha. Higher experimental yields and state yields, especially for Tamil Nadu, indicate some input of irrigation to the crop in the state. For other states, the state yields ranged from 850 to 1340 kg/ha, which indicate the substantial scope to at least double the yields of groundnut in the major rainfed growing states (Andhra Pradesh, Gujarat and Karnataka) considering simulated or experimental potential yields.

Potential yield and yield gap of cash crop cotton

Cotton in India is grown typically in the rainy season in semi-arid regions. The largest area is in

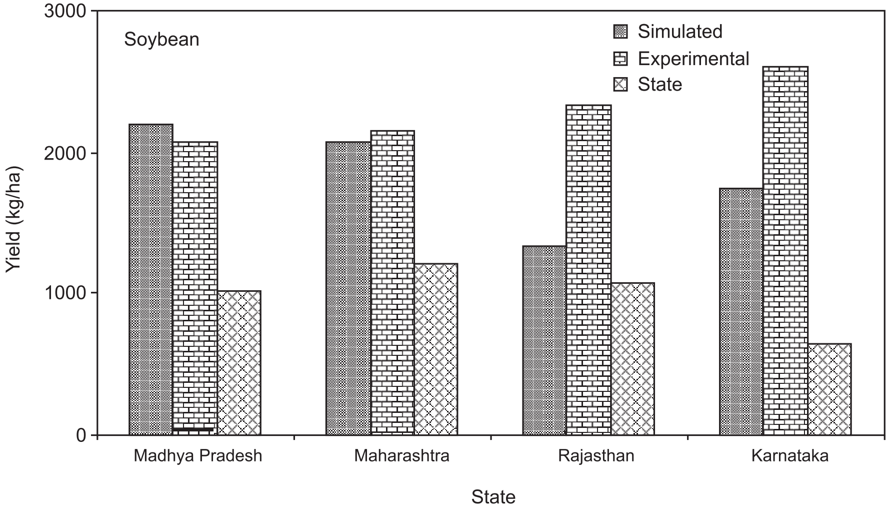


Fig. 6.9. Mean simulated, experimental and measured state-level yields of soybean in India.

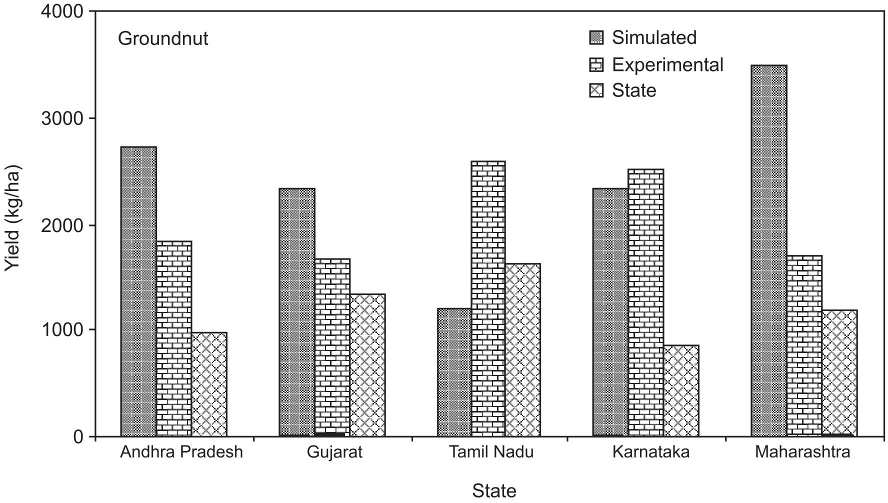


Fig. 6.10. Mean simulated, experimental and measured state-level yields of groundnut in India.

the states of Maharashtra, Andhra Pradesh and Gujarat, followed by Punjab, Haryana, Karnataka and Madhya Pradesh. In the north Indian states of Punjab, Haryana and Rajasthan, the entire crop is irrigated, whereas in other states, it is partially irrigated or rainfed. Almost the entire crop is rainfed in Maharashtra, the largest cotton-cultivating state, accounting for 34% of the cotton area and 27% of national production. The total production of cotton in India is 10 million bales (170 kg each) from 9 million ha area. On average the production of cotton since 1972–1976 has increased from 6.2 million t to 15.7 million t during the period 2002–2006 (Table 6.4). The increase in production was more due to yield increase over the years, from an average value of 140 kg/ha during 1972–1976 to 310 kg/ha during 2002–2006 rather than due to an increase in the area under the crop.

Simulation results showed reasonable potential yields of rainfed cotton in different regions. At the state level, the simulated rainfed potential yields varied from 1400 to 1830 kg/ha. The lowest potential was in the states of Karnataka and Madhya Pradesh, whereas the highest yield was in Andhra Pradesh (Fig. 6.11). All India mean potential yield was 1650 kg/ha. The experimental potential yields also showed considerable variation. On average, the yields were between 980 and 1110 kg/ha in all states except in Andhra Pradesh, where these were more than 1650 kg/ha.

The mean seed cotton yield at the state level was lowest in Madhya Pradesh (370 kg/ha). This was followed by Maharashtra and Gujarat, where the yield level reached up to 500 kg/ha. In the state of Karnataka, the mean yield was 600 kg/ha and was highest in Andhra Pradesh. However, the actual rainfed yields in Andhra Pradesh, Gujarat and Madhya Pradesh would be somewhat lower than these figures because the reported yields also included the data from irrigated regions.

Mean yield gap between simulated rainfed potential yield and the state mean yield was on average 1120 kg/ha. The lowest gap of 800 kg/ha was recorded for Karnataka while the maximum gap was in Gujarat (1210 kg/ha). At the experimental station level, the gap was highest in Andhra Pradesh and Gujarat, while Karnataka again had the lowest gap (Fig. 6.11). The mean gap at this scale was only 640 kg/ha. Thus, in the main rainfed cotton-producing states there is a sufficient gap that can possibly be bridged by improved management in future. On average, it can be concluded that the yield gap is high in the states of Gujarat, Andhra Pradesh and Madhya Pradesh and low in Karnataka.

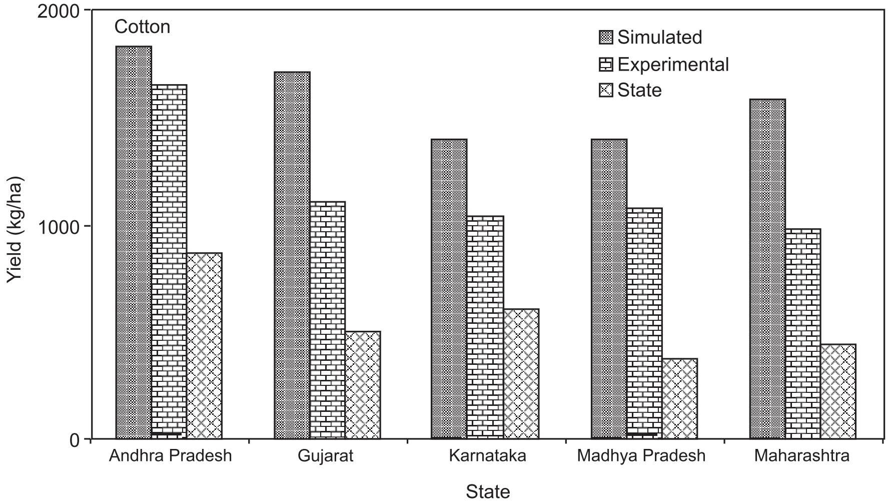


Fig. 6.11. Mean simulated, experimental and measured state-level yields of cotton in India.

Constraints and opportunities for increasing crop yields in India

Extensive land degradation and unfavourable climate are the major abiotic constraints limiting crop production in the rainfed areas of India. Erratic rainfall results in frequent droughts and waterlogging in the rainy-season crops. Both low and high temperatures and drought limit the productivity of post-rainy-season crops, especially legumes. Most of the soils in the rainfed regions of India have low soil fertility caused by soil erosion, continuous mining of nutrients by crops with inadequate nutrient inputs by the farmers. Biotic constraints are also the major yield reducers of rainfed crops. Shoot fly, stem borer and grain mould for *kharif* sorghum, and shoot fly, stalk rot and leaf diseases for *rabi* sorghum are predominant. For pearl millet, downy mildew, smut and rust, and for maize, weeds, rats, termites and stem borers are the major constraints limiting their productivity. For chickpea and pigeonpea, *Helicoverpa*, wilt and sterility mosaic are the major constraints. For groundnut, leaf spot, rust, pod rot and aflatoxin are the major biotic constraints. Boll worm is the major constraint for cotton production. High-yielding improved cultivars resistant to some of these biotic constraints have been developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the national institutes in India and are being promoted for adoption by farmers.

An integrated genetic and natural resource management (IGNRM) approach in the watershed framework is needed to enhance the productivity of rainfed crops in the rainfed areas. Integrated watershed management, comprising improved land and water management, integrated nutrient management including application of micronutrients, improved varieties and integrated pest and disease management, has been evaluated by ICRISAT in several states of India. Substantial productivity gains and economic returns have been obtained by farmers (Wani *et al.*, 2003a,b). Widespread deficiency (80–100% of fields) of micro- and secondary nutrients (zinc, boron and sulfur) have been observed in the farmers' fields in Andhra Pradesh, Gujarat, Rajasthan and Karnataka. Application of micronutrients resulted in a 20–80% increase in yield of several crops, which further increased by 70–120% when micronutrients were applied with adequate amounts of nitrogen and phosphorus (Rego *et al.*, 2007). Thus, improved varieties along with improved management of natural resources have the potential to increase crop production in rainfed areas of India, which need to be promoted and scaled up.

Yield gap of selected crops in north-eastern Thailand

Thailand has a current population of 64 million, which is expected to increase to 69 million by 2025 (United Nations, 2006). Currently, Thailand is a net exporter of rice, cassava, maize and other food items. It imports wheat, soybean and cotton. As Thailand is limited in land area, the future increase in food production must come from an increase in crop yield per unit of land area, from both the irrigated and rainfed regions of the country. North-eastern Thailand (NE Thailand), which has large area under rainfed agriculture, is situated between 14 and 19° N latitude and 101 and 106° E longitude. The area is about 17 million ha or one-third of the whole country. It covers 19 provinces (Fig. 6.12). Despite the same amount of rainfall, NE Thailand is drier than northern and central Thailand because of the short rainy season. Farming is the main occupation and only 20% of the total agricultural area is under irrigation. Cassava, sugarcane, upland rice, maize, soybean and groundnut are the main crops of NE Thailand. However, the cassava area is decreasing because of marketing problems and is being replaced by sugarcane (Land Development Department, 2000; Wangkahart *et al.*, 2005).

Production of rice, maize, soybean and groundnut in NE Thailand has followed a similar trend as in Thailand overall (Table 6.5). From 1993– 1994 to 2002–2003, rice production in Thailand and NE Thailand has increased because of both increase in area and yield per hectare. Area cultivated to maize, soybean and groundnut decreased during the same period. Total production of maize increased primarily due to the increase in yield of the crop. The production of soybean and groundnut decreased from 1993–1994 to 2002–2003 in spite of an increase in productivity of these crops. Current levels of yield of rice, maize, soybean and groundnut in NE Thailand are 1960, 3410, 1420 and 1560 kg/ha, respectively.

Biophysical characteristics of north-eastern Thailand

TOPOGRAPHY AND SOILS North-eastern Thailand or the 'Khorat Plateau' is characterized by a shallow basin (saucer-shaped basin) and slopes rather gently south-eastward. The plateau consists of flat-topped mountain and dissected peneplain surface with undulating features. The elevation varies from 200 to 1000 m above mean sea level (msl). Considering differences in the elevation and geology, NE Thailand can be broadly divided into highlands, uplands and lowlands (Fig. 6.12) (Land Development Department, 2000).

The soils in NE Thailand are characterized by sandy or sandy loam to sandy clay loam texture with low to medium fertility (Land Development Department, 2000). Skeleton soils owing to a shallow laterite layer are widespread in the Sakon Nakon Basin and comprise 13% of NE

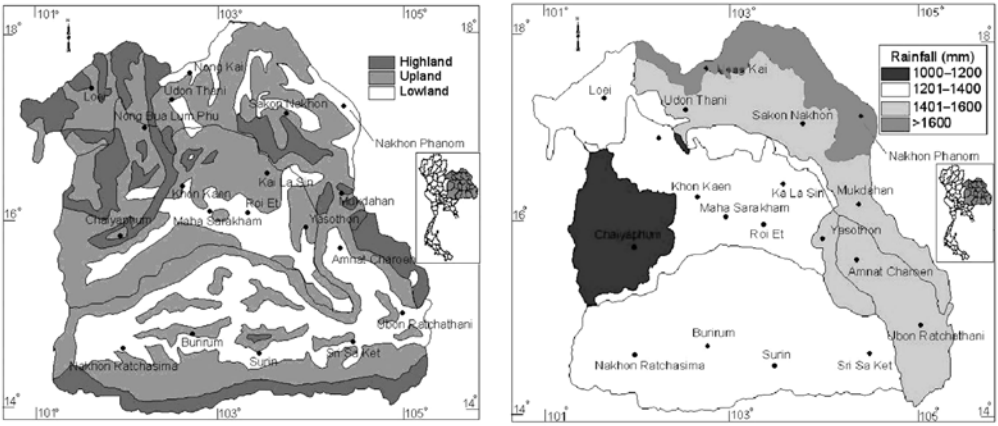


Fig. 6.12. Topography and spatial distribution of rainfall in north-eastern Thailand.

Table 6.5. Area, production and yield of crops in Thailand and north-eastern Thailand[a].

Crops	Area ('000 ha)		Production ('000 t)		Yield (kg/ha)	
	1993–1994	2002–2003	1993–1994	2002–2003	1993–1994	2002–2003
Thailand						
Rice	8389	9905	18304	26295	2180	2660
Maize	1285	1115	3647	4204	2840	3770
Soybean	388	167	520	250	1340	1500
Groundnut	96	69	143	113	1500	1620
North-eastern Thailand						
Rice	4469	4955	7584	9692	1700	1960
Maize	329	279	877	950	2670	3410
Soybean	50	35	69	49	1380	1420
Groundnut	32	26	47	41	1440	1560

[a]Source: FAOSTAT (2006).

Thailand. Saline and sodic soils commonly occur in the plateau and cover about 17% of the region. Fertile soils of the alluvial plain are distributed along the Mekong, Chi and Moon rivers and their tributaries and comprise a rather small area of only 6% of the total NE area. Thus sandy topsoils, salt-affected soils and skeleton soils are the three major problem soils of the north-east. Low soil fertility and erratic rainfall are responsible for the low agricultural productivity of the north-east as a whole (Land Development Department, 2000; Wangkahart *et al*., 2005).

CLIMATE NE Thailand is influenced by a tropical wet–dry monsoonal or tropical savannah climate. The south-west monsoon from May to September brings warm and moist weather from the Indian Ocean to the region. During November to February, the area is influenced by the north-east monsoon from the Eurasian continent, resulting in cooler and dry weather over the whole region. The mean annual rainfall in NE Thailand is 1375 mm. The mean annual temperature in NE Thailand is about 26.7 °C. In the west and the middle of the region, such as Chaiyaphum, Nakhon Ratchasima, Loei, Khon Kaen and Roi Et province, the rainfall is lower than in the east and the north and is about 1000–1400 mm (Fig. 6.12). In the east and the north, such as Nakhon Phanom, Sakon Nakhon, Nong Kai, Ubon Ratchathani, Udon Thani and Mukdahan provinces, the annual rainfall is about 1500–2300 mm. The highest rainfall (2324 mm) is in Nakhon Phanom province.

The year can be divided into three seasons: rainy, winter and summer. The rainy season starts from the end of May or the beginning of June and extends up to the beginning of October (Fig. 6.13). August and September are the high rainfall months. Maximum and minimum temperatures are the highest in April and start dropping thereafter. Winter lasts from mid-October to mid-February. The summer season extends from February to the end of May. Because the north-east region is located far away from the Gulf of Thailand, the summer season is hot and very dry in the region.

Method of yield gap analysis

Yield gap analysis for the four crops was based on the experiment station yield and actual crop yields obtained during 1998 under lowland, upland and highland topographic conditions of NE Thailand. The experiment station yields obtained under a rainfed situation without any nutrient deficiency were considered as the potential yields of rainfed crops. Actual yields were obtained by recording crop yields of farmers in the region under lowland, upland and highland situations. Actual yields were compared with the potential yields to estimate yield gaps of crops for different topographic situations of NE Thailand (Piara Singh *et al*., 2001).

Potential yield and yield gap of crops

Agriculture in NE Thailand is based mainly on rainfed crops (upland crops) such as cassava,

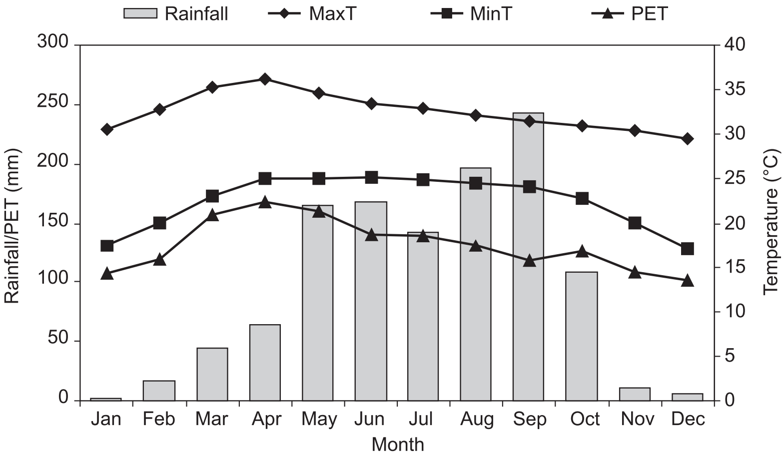


Fig. 6.13. Mean monthly maximum and minimum temperatures and monthly total rainfall and potential evapotranspiration (PET) for Khon Kaen, Thailand.

sugarcane, maize, upland rice, groundnut and soybean, which are important crops of this region. Four crops (rice, maize, soybean and groundnut) were selected to study the yield gap.

RICE Of the total rice area of 10 million ha in Thailand, about 5 million ha area is in NE Thailand (Table 6.5). The yield of rice in NE Thailand is 36% lower than the average rice yield of Thailand. Upland rice in NE Thailand is grown mainly for household consumption. The average experimental yield of rainfed upland rice in NE Thailand is 1490 kg/ha (Fig. 6.14). Farmers' rice yield in the uplands can be increased by about 22% from the current level of their yields with improved practices.

MAIZE Maize is the second most important food crop for human and animal feed after rice. In Thailand, maize has been grown for more than 40 years. Selection and breeding of maize in the country has resulted in higher yields. Of the total production area of 1.1 million ha, about 0.28 million ha is in NE Thailand (Table 6.5). The yields are lower compared with other regions. Experimental yield of maize in NE Thailand is 4710 kg/ha. The farmers' yields from highlands to lowlands increase from 1530 to 3490 kg/ha (Fig. 6.14). Thus the productivity of maize can be increased by 35–200% with improved management from the current levels of farmers' productivity, depending upon the topography.

SOYBEAN In Thailand, soybean cultivation started in 1936. With the expansion of animal husbandry, the requirement for soybean reached about 2 million t/year. From 1993–1994 to 2002–2003, both area and production of soybean decreased; however, the average productivity of soybean in both Thailand and NE Thailand increased (Table 6.5). The experimental yield of soybean in NE Thailand is 1910 kg/ha and the farmers' average yields range from 980 to 1290 kg/ha, depending upon the topography (Fig. 6.14). Thus, the productivity of soybean can be increased by 50–95% with improved management.

GROUNDNUT Both the area and production of groundnut in Thailand have declined since 1993–1994. Currently NE Thailand has only 0.026 million ha under the crop, with a production of 0.041 million t. However, the average productivity of the crop has increased and it is 96% of the average groundnut yield in the country (Table 6.5). The experimental yield of groundnut in NE Thailand is 1740 kg/ha. The farmers' yields in the region ranged from 1160 to 1540 kg/ha (Fig. 6.14). Thus, the farmers' yields can be improved by 13–50% with improved management from the current level of productivity.

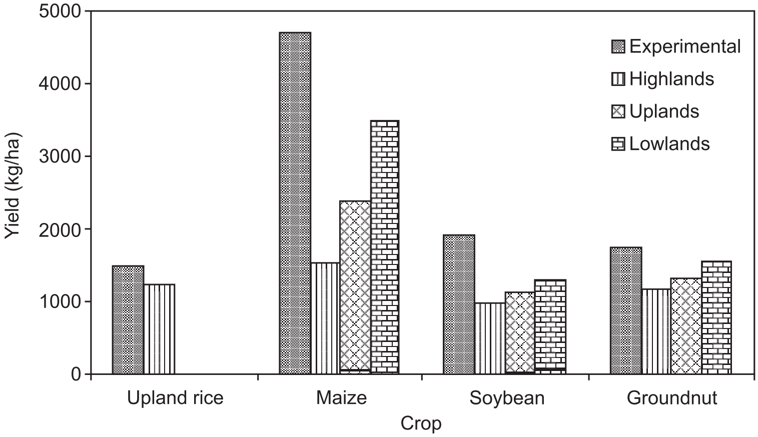


Fig. 6.14. Experimental and actual yields of rainfed crops in north-eastern Thailand.

Constraints and opportunities for bridging the yield gaps in north-east Thailand

Major constraints that limit the yields of crops in NE Thailand are frequent droughts and floods, low soil fertility, soil erosion and land degradation, poor soil water conservation practices, low-yielding crop varieties, shortage of labour, poor agricultural extension for technology transfer, uncertainty of prices and marketing problems, uncertainty of tenure as a disincentive to invest in land development and poor credit facilities and high interest rates by private moneylenders. Bridging the yield gap of upland cropping systems would require adoption of improved soil and water conservation practices, integrated soil fertility management including the greater use of legumes, improved cultivars, a stable land tenure system, affordable credit facilities and assured prices and marketing of agricultural produce. The integrated watershed management approach adopted at Tad Fa watershed site in NE Thailand in collaboration with ICRISAT demonstrated that soil, water and nutrient management (SWNM) and crop management practices not only reduced land degradation but also substantially enhanced crop yields of the farmers (Wangkahart *et al.*, 2005).

Yield gap analysis of crops in northern Vietnam

Northern Vietnam comprises approximately three-quarters uplands (mountains and hills) and one-quarter lowland. The total population of Vietnam is 87 million, which ranks 7th in Asia and 12th in the world and is expected to increase to 106 million by 2025 (United Nations, 2006). The massive population growth which has already taken place in Vietnam has resulted in greater urbanization with more agricultural land being transferred to non-agricultural use. Under such circumstances, pressure on uplands and midlands is increasing for food production to fulfil the local demands and to achieve food security for millions of poor residing in Vietnam. The Vietnam government now has a greater challenge on hand to achieve food security by 2025. Therefore, the uplands are expected to produce more food for meeting the local needs and supply to other regions.

The major crops of northern Vietnam are rice, sweet potato, maize, tea, groundnut and soybean. Of these, only rice and groundnut are exported to other countries. In 2005, rice and groundnut were exported to the extent of 5.3 million t and 0.05 million t, respectively. The other crops exported in the same year were coffee (0.9 million t), rubber (0.6 million t), pepper (0.1 million t), cashew nut (0.1 million t) and tea (0.09 million t). Vietnam normally imports wheat and cotton to meet its domestic needs (General Statistics of Vietnam, 2007). In the lowlands of Vietnam mainly annual crops are grown, while in the uplands annual and perennial crops are grown. In the mountains, legume crops such as groundnut, soybean and mung bean are grown after rice. These are important crops as a source of oil and protein for the mino-ethnic people and fodder for cattle and also for improving soil fertility. Tea and cassava are also common crops as these are drought tolerant and have the ability to grow under poor farm management practices, poor soil fertility and low inputs. Cassava is a staple food when rice production is low and it also provides feed for animals in the upland area.

Climate of northern Vietnam

The climate of northern Vietnam is monsoonal in nature. The south-west monsoon occurs from May to October, bringing heavy rainfall and the temperatures remain high. November to April is the dry season, with a period of prolonged cloudiness, high humidity and light rain. The total annual rainfall ranges from 1100 to 3000 mm (Fig. 6.15). The length of the growing season ranges from 180 to 365 days (Fig. 6.16), which provides the opportunity to grow two crops in a year during spring and summer or autumn–winter. Mean annual temperature is 25 °C, with a mean maximum of 35 °C (in August) and minimum of 12 °C (in January). The climate of northern Vietnam is characterized by four seasons, namely spring, summer, autumn and winter. The spring season is from February to May, summer from June to July, autumn from August to October, and winter from November to January. Six benchmark sites selected for yield gap analysis are located in northern Vietnam, where maximum rainfall occurs from July to September. June and July are the hottest months, while December and January are the coldest months of the year (Chuc *et al.*, 2006).

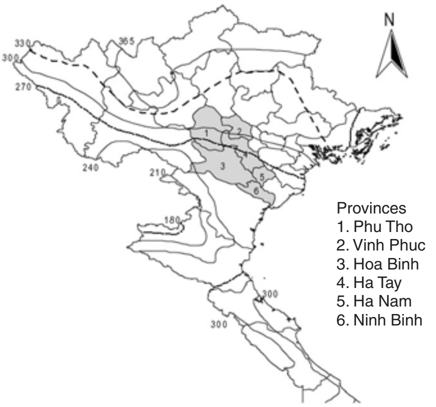


Fig. 6.16. Length of growing season and selected provinces in northern Vietnam.

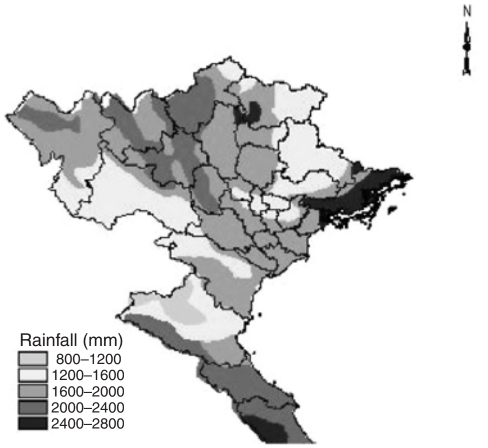


Fig. 6.15. Annual rainfall in northern Vietnam.

Area, production and productivity of selected crops in northern Vietnam

Northern Vietnam includes 31 provinces and most of them have an area under soybean, groundnut and maize. There has been a general increase in area, production and productivity of soybean in northern Vietnam since 1995–1996. Between 1995–1996 and 2004–2005, the soybean production increased 2.52 times, which was because of a 72% increase in area and a 47% increase in crop yield (Table 6.6).

The groundnut area also increased in most of the provinces in north Vietnam. Between 1995–1996 and 2004–2005, the groundnut production doubled because of a 26% increase in area under the crop and a 63% increase in yield over the same period (Table 6.6). Since 1999, plastic mulch technology for soil moisture conservation and increasing soil temperature during germination and early plant growth stage and integrated farm management practices were applied in all the provinces of the Red River Delta. It has improved productivity of groundnut by 30–70% as compared with no mulching and traditional practice (Chinh *et al.*, 2000).

Maize is the main crop in the mountainous area of northern Vietnam. Since 1998, these

Table 6.6. Area, production and yield of soybean, groundnut and maize in northern Vietnam during 1995–1996 and 2004–2005[a].

	Soybean		Groundnut		Maize	
Attribute	1995–1996	2004–2005	1995–1996	2004–2005	1995–1996	2004–2005
Area ('000 ha)	72.5	124.5	61.8	78.1	323.6	449.0
Production ('000 t)	65.1	164.3	69.5	143.0	663.6	1377.2
Yield (kg/ha)	900	1320	1120	1830	2050	3070

[a]Source: FAOSTAT (2006).

provinces have been growing hybrid maize cultivars and have applied improved crop management practices promoted by the Vietnam Maize Research Institute. Between 1995–1996 and 2004–2005, maize production has more than doubled, which was because of a 39% increase in area under the crop and a 50% increase in yield during the same period.

Yield gap analysis of crops for the six selected provinces

The six provinces selected for the yield gap study were Phu Tho, Vinh Phuc, Ha Tay, Hoa Binh, Ha Nam and Ninh Binh (Fig. 6.16). Ha Tay, Ha Nam, Ninh Binh and Vinh Phuc provinces are located in the Red River Delta region. These provinces have both upland and lowland areas sown to annual and perennial crops. The rotations of maize–soybean, groundnut–maize, rainfed rice–maize and soybean–mung bean and mono-cultured sugarcane, cassava or tea are the main cropping systems practised in the watershed area of the six provinces, where legumes and maize appear in most of the crop rotations. Thus, maize and legumes play an important role in the existing rainfed farming systems. The farmers normally grow two main crops in a year under rainfed situations. Depending upon the amount of rainfall received, the first crop is sown in February to March and harvested by the end of May or during June. The second crop is sown in July and harvested in November. Yield gap analysis was carried out for soybean, groundnut and maize for the selected provinces.

Methods of yield gap analysis

The estimation of potential rainfed yields and yield gaps was based on simulated yields, experimental station yields and province yields – all obtained under rainfed situation. The potential yields of soybean, groundnut and maize were simulated using DSSAT v3.5 (Hoogenboom *et al.*, 1999) crop models as previously described in the section on yield gap analysis for India. The models were tested and validated using data of three experiments each of maize (2000 spring, 2000 summer and 2001 spring season), soybean (2000, 2001 and 2002 spring season) and groundnut (2000, 2001 and 2002 season) conducted at the Than Ha watershed site in Hoa Binh province (Chuc *et al.*, 2006). Rainfed potential yields of crops were simulated using weather data of 28 years for the five locations (Vinh Phuc, Ha Nam, Ninh Binh, Ha Tay and Phu Tho) and 10 years for the Hoa Binh.

Long-term yield data of yield maximization trials were also available for each crop and benchmark site. These data were averaged over the time period and compared with mean simulated yields and province-level mean yields for the benchmark sites to quantify the yield gaps for each crop (Chuc *et al.*, 2006).

Potential yields and yield gap of crops

SOYBEAN The mean simulated potential yield of soybean across provinces ranged from 1760 to 2240 kg/ha during the spring season, the lowest being at Phu Tho and the highest at Ha Nam (Fig. 6.17). The overall mean potential yield across provinces was 2000 kg/ha. The experimental yields ranged from 1600 to 1900 kg/ha across states, the lowest being at Phu Tho and the highest at Ha Tay. The mean experimental yield across provinces was 1770 kg/ha. Similarly, the province yields were also variable, with overall mean of 1360 kg/ha. On average, the yield gap between the simulated and province yield

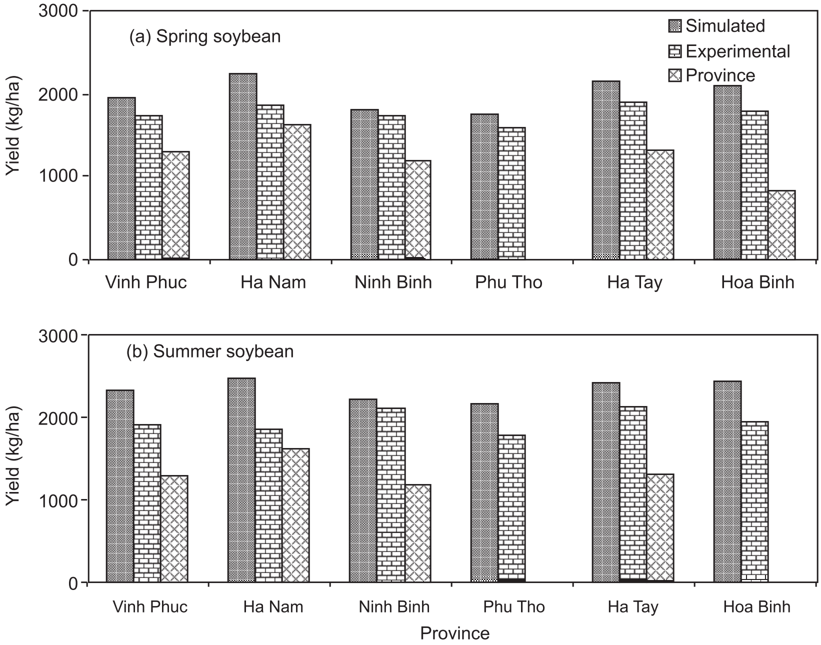


Fig. 6.17. Simulated potential yield, experimental station yields and province mean yield of rainfed soybean in (a) spring and (b) summer seasons at benchmark locations in northern Vietnam.

was 640 kg/ha and between the experimental and province yields it was 410 kg/ha.

In general, the potential yields of soybean were higher during the summer season than during the spring season. The mean simulated potential yield across provinces was 2350 kg/ha with a range of 2160 to 2480 kg/ha. Similarly, the mean experimental yield was 1960 kg/ha, ranging from 1790 to 2140 kg/ha across provinces. The mean yield gap between the simulated potential and the province yield was 1010 kg/ha and between experimental and province yield it was 600 kg/ha.

GROUNDNUT As groundnut is more drought resistant during the initial stages of its growth under rainfed conditions, the spring season for groundnut starts earlier as compared with soybean and maize. During the spring season, simulated potential yields of groundnut across six provinces ranged from 3740 to 4700 kg/ha, with an overall mean of 4170 kg/ha. Whereas, the experimental potential yields ranged from 2550 to 3400 kg/ha with an overall mean of 3010 kg/ha (Fig. 6.18). This indicates that even the experimental yields are below the simulated potential yields by about 1100 kg/ha in the provinces. The province yields of groundnut ranged from 1180 to 2200 kg/ha with an overall mean of 1520 kg/ha. The yield gap between the simulated and province yield was 2650 kg/ha, and between experimental and province yield it was 1490 kg/ha.

During the autumn–winter season, simulated potential and experimental potential yields were lower than those obtained during the spring season (Fig. 6.18). Simulated potential yields ranged from 2910 to 3920 kg/ha with an overall mean of 3530 kg/ha, whereas the experimental yields ranged from 2300 to 2800 kg/ha with an overall mean of 2620 kg/ha. The yield gap between the simulated and province yield was 2010 kg/ha, and between experimental and province yield it was 1100 kg/ha. These results indicate that the groundnut yields in the six provinces during the spring and autumn–winter seasons can be more than doubled with improved management practices.

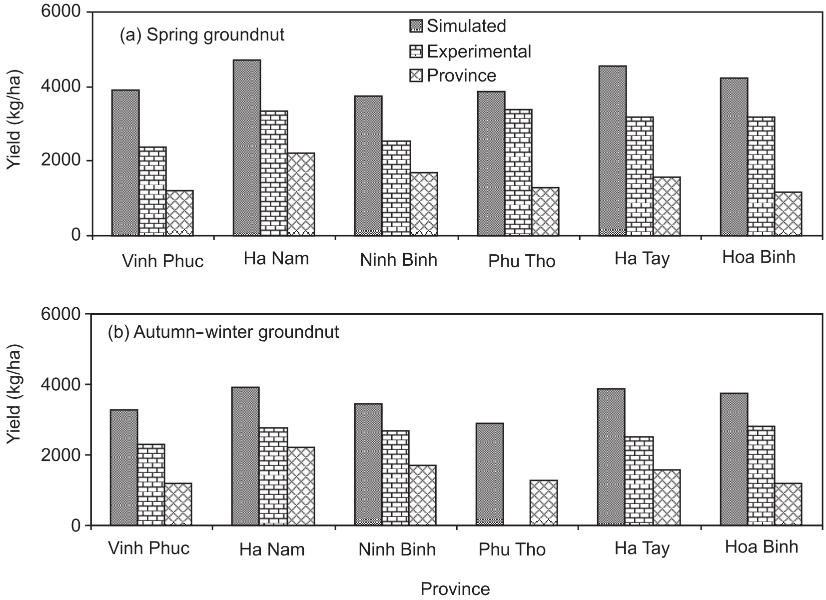


Fig. 6.18. Simulated potential, experimental and province mean pod yields and yield gap of rainfed groundnut in (a) spring and (b) autumn–winter seasons at selected sites in northern Vietnam.

MAIZE Maize is normally sown in spring and summer in the rainfed area of northern Vietnam. During the spring season, simulated potential yields of maize ranged from 4800 to 5430 kg/ha across six provinces, with an overall mean of 5030 kg/ha (Fig. 6.19). The province yields of maize ranged from 2660 to 4180 kg/ha with an overall mean of 3380 kg/ha. The yield gap between the simulated and province yield was 1650 kg/ha. During the summer season, simulated potential yields were higher than those obtained during the spring season (Fig. 6.19). Simulated potential yields during the summer season ranged from 5250 to 5570 kg/ha across six provinces, with an overall mean of 5370 kg/ha. The yield gap between the simulated and province yield was 1990 kg/ha.

Constraints and opportunities for bridging the yield gaps in northern Vietnam

The main constraints for low yields of rainfed crops in northern Vietnam are undulating topography, poor soil fertility, drought and little adoption of improved soil, water, nutrient, crop and pest management practices, leading to inefficient use of natural resources such as rainfall (Wani *et al.*, 2003a). Socio-economic factors (socio-economic status, farmers' traditions and knowledge, family size, household income and expenses) and institutional and policy factors such as government policy, product prices, credit, input supply and market, land tenure and linkage factors consisting of competence and facilities of extension staff; integration among research, development and extension; farmers' resistance to new technology; knowledge and skills; and weak linkages among public, private and non-governmental extension staff also contribute to the problem significantly.

Large yield gaps between current province and potential yields of soybean, groundnut and maize in northern Vietnam could be bridged through large-scale adoption of improved soil, water, crop and pest management options available. Traditionally much emphasis has been put on developing new cultivars; however, the findings from a number of studies have suggested that without appropriate soil, water and nutrient management options the true potential of improved cultivars cannot be realized. Because of increasing competition for land by other sectors of the economy, future increase in crop production can be achieved only by enhancing

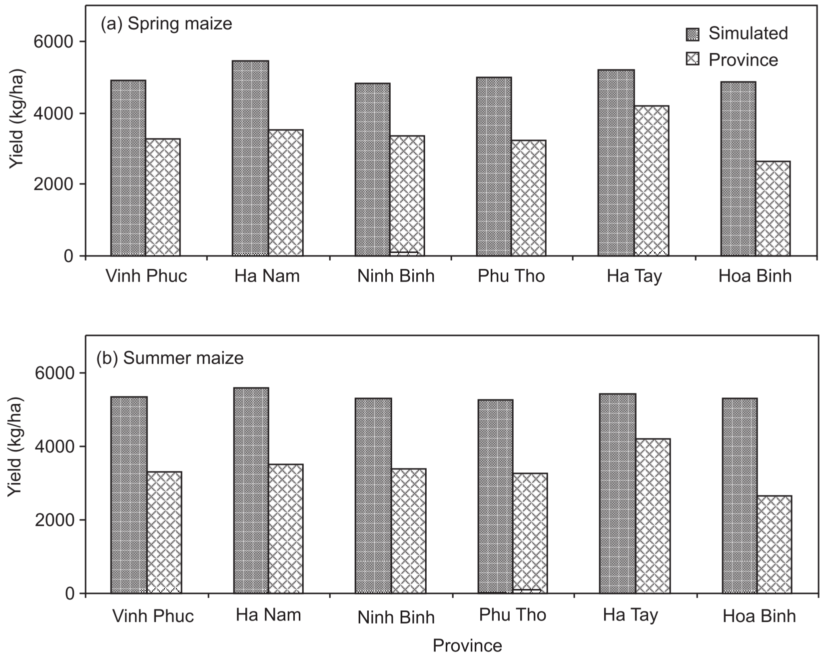


Fig. 6.19. Simulated potential, province mean pod yields and yield gap of rainfed maize in (a) spring and (b) summer seasons at selected sites in northern Vietnam.

productivity per unit of land area rather than area expansion. An integrated watershed management approach, which has been evaluated by the Vietnam Agricultural Science Institute (VASI) and ICRISAT at benchmark watersheds in Hoa Binh and Vinh Phuc provinces, has shown the large potential for reducing land degradation and increasing productivity of crops (Wani *et al.*, 2003a). While no major breakthrough is expected immediately, reducing the yield gap alone in the country could supply 20–60% of the increased annual food demand by the year 2025 (FAO, 2004).

Yield Gap Analysis of Crops in the WANA Region

The WANA region is an enormous and diverse area, with Morocco in the west, Pakistan and Afghanistan in the east, Turkey and Iran in the north and Ethiopia and Sudan in the south. The WANA region covers about 125 million ha of rainfed agricultural land with annual rainfall ranging from 200 to 600 mm with high variability in space and time (Fig. 6.20). The WANA region includes Afghanistan, Algeria, Bahrain, Djibouti, Egypt, Eritrea, Ethiopia, Gaza Strip, Iran, Iraq, Jordan, Kuwait, Lebanon, Libya, Mauritania, Morocco, Oman, Pakistan, Qatar, Saudi Arabia, Somalia, Sudan, Syria, Tunisia, Turkey, United Arab Emirates and Yemen. Yield gap analysis was carried out for key locations in Morocco, Syria and Turkey.

The soils of the region are diverse, and seven major soil groups account for 86% of the above-mentioned rainfed areas. Agricultural soils of the region are predominantly derived from limestone residuum, thus calcareous with very variable texture, depth, slope and stoniness (Kassam, 1988). In general, soil organic matter levels are low and in some soils, silty and sandy in particular, structural stability is poor, causing surface crusting by rainfall, resulting in serious problems in seedling emergence and surface run-off. Also phosphate and nitrogen deficiencies are common throughout the WANA region. Responses to micronutrients have been observed but are not

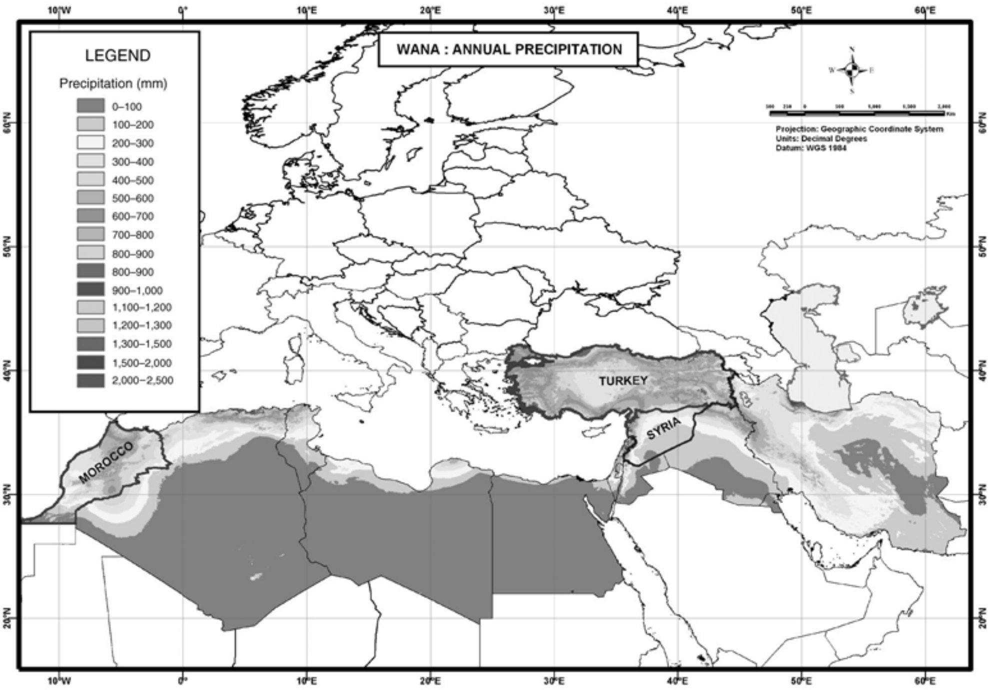


Fig. 6.20. WANA region rainfall isohyets.

widespread in rainfed agriculture. Boron toxicity has been recorded recently as a problem in some parts of the WANA region (e.g. major rainfed wheat-growing areas in central plateau of Turkey) (Harris, 1995).

The climate of the WANA region is characterized by cool (in lowlands) to cold (in highlands) winter and warm to hot arid summer. Locally, conditions are modified considerably by topography and by continental (west Asia) or maritime (North Africa) effects. Precipitation, whether as rain or snow in highland areas of west Asia, is variable in space and unreliable in time and often deficient in amount. In general, coastal areas are wettest and the amount decreases rapidly with distance inland. On average, rain starts in autumn (September–October), reaches a peak in January or February and decreases rapidly until April (in lowlands) or May or June (in highlands). However, year-to-year variability in rainfall distribution is often experienced. The first rains may be delayed by as much as 2 or 3 months and a similar uncertainty attaches to the time the rains end.

Crop production systems in WANA

Rainfall and other sources of water in combination with temperature, soils and socio-economic factors are the major determinants for the multiplicity and complexity of the production systems in the WANA region. These systems are mainly based on cereals (barley in drier areas, wheat in more favourable areas) and legumes (lentil, chickpea and faba bean and a small portion of forages) in rainfed areas and on summer crops in the irrigated areas (FAOSTAT, 2004). In the region, integration with livestock, mainly sheep and goats, is important for nutrient cycling and fertilization of the soils, which eventually improve the soil water use (Cooper *et al.*, 1987). Fallow is still practised mostly in high-elevation cold areas in rotation with cereals. Introduction of forage legume production in rotation with barley has been proved successful but the adoption rate is still low because of socio-economic conditions of the farmers (Osman *et al.*, 1990; Bounejmate *et al.*, 2002). All winter-sown crops are increasingly exposed to drought in the spring or early summer when evaporative demand is high, mostly at flowering and grain-filling stages, and are largely dependent on the stored soil moisture to complete their growth cycles (Cooper *et al.*, 1987). Intercropping of cereals or legumes between young olive trees (until fruit production) is becoming a common practice in the wetter areas because of economic considerations of farmers. Almost 30% of the above-mentioned cropped areas in the WANA region are now irrigated and over half the region's crop production is produced under irrigation. The WANA region has about 137 million ha arable land, of which 35 million ha is sown to wheat (FAOSTAT, 2002). About 20–30% of the crop is irrigated and the rest is under rainfed conditions. Productivity of wheat in rainfed areas is still low, around 1.0 t/ha in general, ranging from 0.5 to 1.5 t/ha on average. However, wheat production in the region increased from 47 million t in 1985 to 81 million t in 2004 (FAOSTAT, 2004), which is quite a high increase, bringing certain countries such as Syria and Turkey into self-sufficiency in wheat production on the basis of improved management practices combined with the use of improved varieties and irrigation. But it is unlikely that such expansion in production through irrigation can be sustained without proper water and land management strategies.

Wheat is mostly grown in the 300–600 mm rainfall zone throughout the region. While irrigated areas may produce far higher yields and marketable surpluses, the overall value of rainfed production (about 50% of the total production given above) is much greater than its market value owing to social and other indirect benefits associated with these systems. Rainfed production is dependent on low and extremely variable rainfall and therefore productivity is low and unstable. This is further affected by frequent droughts and continuing land degradation. Research has focused on ways to improve the water availability to crops in rainfed areas. Given the limited ability to utilize new sources of water in the region, a major challenge is sustainable increase in productivity by improving the efficiency of the on-farm use of the limited water resources available. Among the most relevant are those countries with extensive rainfed areas, including Algeria, Morocco and Tunisia in North Africa and Iraq, Jordan, Pakistan, Syria and Turkey in west Asia. Thus, yield gap analysis was carried out in the selected countries of Morocco, Syria and Turkey, representing major agroecologies for the wheat crop, which is the major staple cereal in the region. The general framework for situating wheat crop zones in relation to rainfall is shown in Fig. 6.21.

Analyses of potential yields and yield gaps

To analyse the potential yields and yield gaps of wheat, data were collected from the partner institutions. These included data on experimental yields obtained with improved agronomic

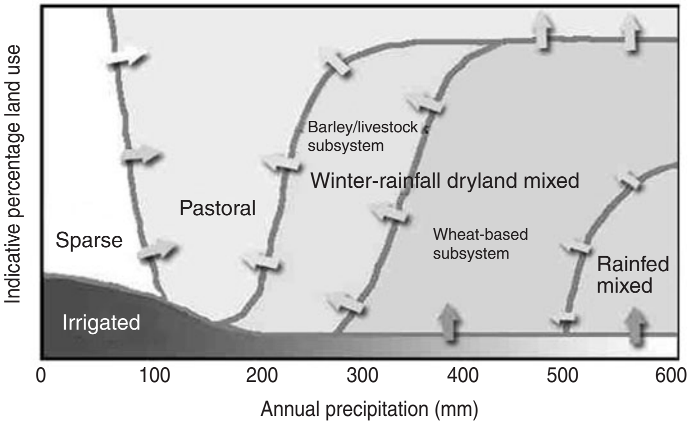


Fig. 6.21. General 'ICARDA' framework for relationship between production systems and precipitation.

management (potential yields) at research stations and simulated potential yields using a cropping systems simulation model on the basis of improved wheat varieties grown in farmers' fields during the period of 10–12 years, depending on the data availability of the three countries (CropSyst) (Stockle *et al.*, 1994; Pala *et al.*, 1996). Farmers' yields were obtained from farmers' fields in the vicinity of on-farm yield trials conducted by researchers; state farm yields were obtained from the large-scale seed production fields of state farms (in Turkey only); and district- or province-level actual yields were obtained from the agricultural statistics of each country (Syria and Turkey only). Morocco in North Africa for mild lowlands and mild highlands, Syria in west Asia for mild lowlands and Turkey in west Asia for cold highlands were selected for the yield gap analysis as major representation of the region (Fig. 6.20).

Wheat area, production and productivity are given in Table 6.7 for the selected major countries representing different agroecologies of the WANA region. Wheat area increased by 16.9% while wheat production increased by 73.6% between 1985 and 2004 because of the yield increase of 48.3% in the WANA region (FAOSTAT, 2004). Since these data are given as an average of irrigated and rainfed regions together, we carried out an analysis of the situation for rainfed regions as follows.

About 75% of the total wheat area is under rainfed conditions; thus the mean wheat area of WANA would be 24,284,000 ha while the irrigated area is 8,094,000 ha. The irrigated wheat yield could be accepted as 3.5–4.0 t/ha on average. Therefore, mean rainfed yield could be calculated as 1.27–1.41 t/ha for the entire WANA region, which is still quite low, although there is a remarkable increase in yield and production of wheat since 1985.

Morocco

Since 1985, the wheat area in Morocco has increased by 61.7%, while production and yield of wheat has increased by 135% and 45.3%, respectively. There is a good potential for further increases in yield with the adoption of improved varieties and agronomic management practices (Table 6.8). In Morocco, two sources of data have been used to calculate the yield gap. In the first case, the data of the WANA Durum Improvement Network Project (WANADIN, 2000) have been used to calculate the yield gaps on the basis of farmers' yields around the research stations compared with the research station yields (Table 6.8).

Potential yield obtained from the research stations under improved management practices is 61–153% more than the farmers' yield. The highest yield increase was obtained in the most

Table 6.7. Area, production and yield of wheat during 1985–2004 in the WANA region[a].

Countries	1985	1990	1995	2000	2004	Mean
Wheat area harvested (million ha)						
Morocco	1.894	2.719	1.968	2.902	3.064	2.509
Syria	1.265	1.341	1.644	1.679	1.831	1.552
Turkey	9.275	9.432	9.400	9.400	9.400	9.381
WANA all	30.105	31.823	32.718	32.034	35.208	32.378
Wheat production (million t)						
Morocco	2.358	3.614	1.091	1.381	5.540	2.797
Syria	1.714	2.070	4.184	3.105	4.537	3.122
Turkey	17.032	20.022	18.015	21.009	21.000	19.416
WANA all	46.691	58.586	62.872	66.484	81.067	63.140
Wheat yield (kg/ha)						
Morocco	1245	1330	555	475	1810	1080
Syria	1355	1545	2545	1850	2475	1955
Turkey	1835	2120	1915	2235	2235	2070
WANA all	1550	1840	1920	2075	2300	1950

[a]Source: FAOSTAT (2004).

Table 6.8. Important wheat-growing regions of Morocco and mean yield gap (during 1990–2000)[a].

Region	Precipitation (mm)	Potential yield (kg/ha)	Farmers' yield (kg/ha)	Yield gap/increase over farmers' yields (kg/ha)	(%)
Loukos	>600	8560	4700	3860	82
Douyet	450–600	5400	3350	2050	61
Marchouch	350–450	5230	3100	2130	69
Settat	250–350	4550	1800	2750	153
Tessaout	<250[b]	6270	3500	2770	79

[a] Source: WANADIN (2000); [b]irrigated.

important semi-arid rainfed areas of Morocco, which is Chaouia-Doukkala provinces (Settat) with variable and limited rainfall.

In the second case, a cropping systems simulation model (CropSyst) (Stockle *et al.*, 1994; Pala *et al.*, 1996) has been used with the agroclimatic data from semi-arid regions (250–350 mm rainfall) given above (Settat region), to identify the wheat yield gap during 1994–2003 cropping seasons on the basis of district/province yield means compared with potential yields coming from research stations and crop simulations on the basis of using improved wheat cultivars grown by farmers with given daily rainfall and soil characteristics with recommended nitrogen fertilizer without pest and disease effects during the 10-year period between 1995 and 2004.

Average yields and the gaps among the farmers, research stations and simulated potential values are presented in Fig. 6.22. In the figure, yield gap I represents the gap between the research station (2190 kg/ha) and farmers' yields (1105 kg/ha in Settat and 1220 kg/ha in Berrechid), measured as 98 and 80% increases over the farmers' yields for Settat and Berrechid sites, respectively. The gap between farmers' and simulated potential yield (3390 kg/ha) is presented as yield gap II, as 207 and 178% yield increases over the farmers' yields for Settat and Berrechid sites, respectively.

Syria

Wheat is grown on about 1.5 million ha or 27% of the total cultivated land in Syria, mainly

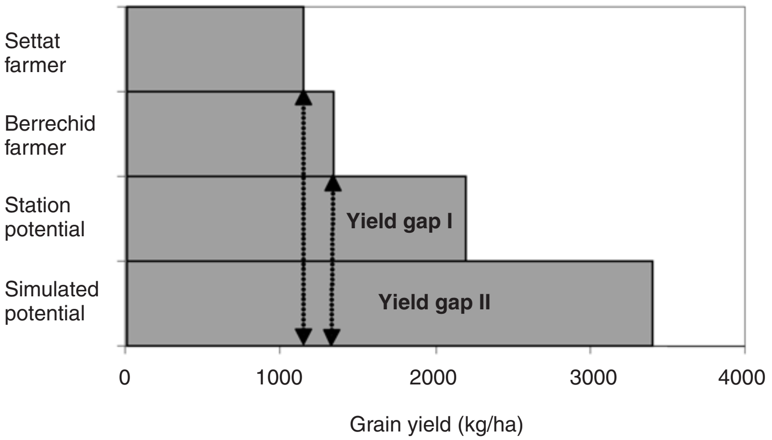


Fig. 6.22. Average wheat yield gap under rainfed conditions in Settat–Berrechid region of Morocco during the 1995–2004 seasons.

under rainfed conditions (300–500 mm annual rainfall), which are increasingly experiencing supplemental irrigation, while drier (<200 mm) areas are fully irrigated (SCBS, 1998). Since 1985, wheat acreage of the country has increased by 45%, while production and yield of wheat increased by 164% and 83%, respectively. Similar to Morocco, there is also a good potential for further increases in yield with the adoption of the improved varieties and agronomic management practices (Table 6.9). In Syria, potential yield obtained from the research stations under improved management practices could on average increase wheat yield over the farmers' yield level by 67–85%. Similar to Morocco, the highest yield increase was obtained in the driest rainfed areas of Syria, which is Zone 2 with variable and limited rainfall, covering about 13% of the country, as similar to Zone 1 (a and b), which covers about 15% of the country. Again improved management practices together with improved varieties have to be adopted by farmers to close the yield gap for sustainable wheat production.

As Zone 1b is the major wheat-producing area of Syria, potential yields were simulated for this zone for 1994–2005 using a simulation model (CropSyst). Farmers' mean yields and research station trials' yields for the Aleppo province and simulated potential grain yields under rainfed conditions for Tel Hadya, Aleppo (long-term average rainfall of 325 mm), representing Zone 1b, are shown in Fig. 6.23. The yield gap between the research station (3675 kg/ha) and farmers' fields (2020 kg/ha), represented as yield gap I, measured a 82% increase over the farmers' yields. The yield gap between farmers' yield (2020 kg/ha) and simulated potential yield (4540 kg/ha), represented as yield gap II, measured a 125% yield increase over the farmers' yields.

Table 6.9. Important wheat-growing regions of Syria and mean yield gap (mean for 1986–2000)[a].

Region	Rainfall (mm)	Research station yield (kg/ha)	Farmers' yield (kg/ha)	Yield gap/increase over farmers' yields	
				(kg/ha)	(%)
Zone 1a[b]	>350	5855	3500	2355	67
Zone 1b[b]	300–350	4935	2930	2006	68
Zone 2[b]	250–300	2165	1170	995	85
Irrigated	200–300	5010	2750	2260	82

[a] Source: WANADIN (2000); [b] rainfed.

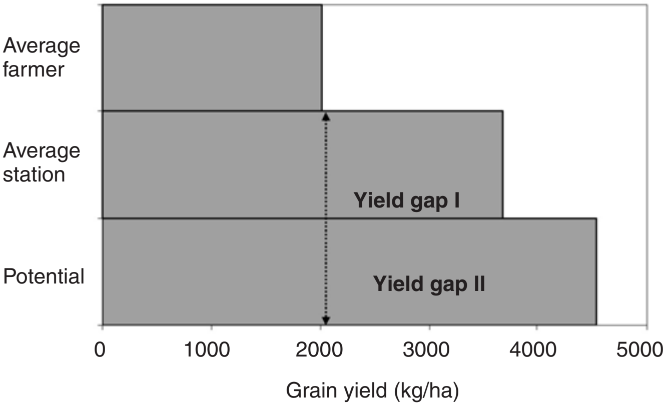


Fig. 6.23. Average wheat yield gap in Aleppo province, Syria during the 1994–2005 cropping seasons.

Turkey

Since 1985, wheat acreage of the country increased by 1.3% only, while production and yield of wheat increased by 23.3% and 21.83%, respectively. However, yield increases have not been as high as for other countries of the region. As most of the wheat is produced in dry, marginal rainfed areas, the yield and production cannot be increased further unless improved agronomic management practices are applied by most of the farmers (Table 6.10). Similar to Morocco and Syria, there is also a good potential for further increases in yield with the adoption of the improved varieties and agronomic management practices, as evident from the yield gaps (Table 6.10).

In central Anatolia (250–500 mm rainfall zone), which is a major wheat-production area of Turkey, the CropSyst simulation model was used to assess potential yields for the 1991–2001 cropping seasons using improved wheat cultivars grown by farmers with recommended nitrogen fertilizer without pest and disease effects. The simulated potential, the research stations' and farmers' mean yields under rainfed conditions are shown for the representative site, Ankara (long-term average rainfall of 360 mm) in central Anatolia, in Fig. 6.24. Yield gap between the research station (2810 kg/ha) and farmers' field (1825 kg/ha), represented as yield gap I, measured a 54% yield increase over the farmers' fields. The gap between farmers' yield (1825 kg/ha) and simulated potential yield (3435 kg/ha), represented as yield gap II, measured a 88% yield increase over the farmers' yields.

Similar to other regions of the WANA, improved management practices together with improved varieties have to be adopted by farmers to close the yield gap for sustainable wheat production.

In summary, the results of the representative areas of three countries of WANA showed the importance of improved soil and crop management practices combined with the use of improved crop varieties, particularly in drier areas, to fill the yield gap for wheat crop for better income and livelihood of the rural communities (Cooper *et al.*, 1987; Harris *et al.*, 1991; Pala *et al.*, 2000; van Duivenbooden *et al.*, 2000).

Major constraints and opportunities for bridging the yield gaps in WANA

The average landholding in the WANA region is 0.5–2 ha. Productivity in such small areas could not be increased easily because of high input costs. Additionally, improved management practices have not been adopted by farmers in the region because of socio-economic factors. Identified constraints include unfavourable growing conditions, unavailability of improved seed and adequate machinery, unawareness of the improved technologies and lack of resources. Therefore, many countries in the WANA region, except Syria and Turkey, have to import wheat for their increasing demand.

Research at the International Center for Agricultural Research in the Dry Areas (ICARDA) and at other regional and national research institutes has led to the development of appropriate technologies and management options for increased water use efficiency, including crop and soil management practices,

Table 6.10. Important wheat-growing regions of Turkey and mean yield gap from the highest yields from state farms and research stations (during 1990–2001)[a].

Region	Rainfall (mm)	Farmers' yield (kg/ha)	State farm highest (kg/ha)	Research station highest (kg/ha)	Yield gap/increase over farmers' yields			
					State farm		Research station	
					(kg/ha)	(%)	(kg/ha)	(%)
Central Anatolia (N)	300–500	2020	2600	3260	580	29	1240	61
Central Anatolia (E)	400–500	1695	2820	3135	1125	66	1440	85
Central Anatolia (S)	250–500	1790	2550	2745	760	42	1180	66
South-eastern Anatolia	200–500	1630	4485	4900	2855	175	3270	201
Eastern Anatolia	450–600	1185	2870	3150	1685	142	1965	166

[a]Source: N Zencirci, Wheat Project Coordinator, Turkey.

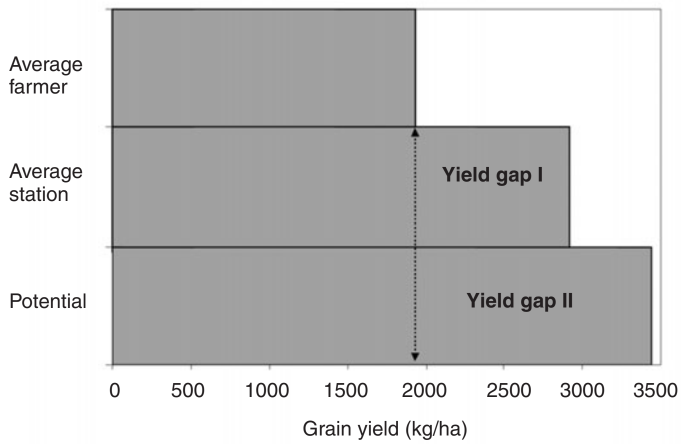


Fig. 6.24. Average wheat yield gap in Turkey (Ankara, Central Anatolia) during 1991–2001 seasons.

improved germplasm and on-farm water management options. One option that has the potential to provide large productivity gains is the use of supplemental irrigation in rainfed crops. Supplemental irrigation of wheat in rainfed areas where water sources are available can boost the crop productivity by three to four times. As a result of research conducted by ICARDA (Oweis *et al.*, 1998, 1999, 2000; Zhang *et al.*, 1998) in collaboration with the National Agricultural Research Systems (NARS), policies are being developed to support the implementation of supplemental irrigation to enhance rainfed agriculture and to better use the limited available water resources. It is also a potential measure for alleviating drought and conserving the natural resource base. There is still a great potential for yield increases in rainfed wheat in the WANA region with the dissemination of improved varieties associated with improved soil and crop management practices such as appropriate crop rotation, timely tillage with conservation practices, timely sowing associated with appropriate sowing method, rate and depth, optimum fertilization, weed and pest control, and appropriate harvest and postharvest handling (Avci *et al.*, 1987; Durutan *et al.*, 1989; Karaca *et al.*, 1989; Harris *et al.*, 1991; van Duivenbooden *et al.*, 2000; Pala *et al.*, 2004; Avci, 2005; Pala, 2005).

Modern bread wheat (*Triticum aestivum)* has been well adapted for survival and production in water-limited environments. Adaptation to various environments has been assisted through selection and cross-breeding for traits that contribute to high and stable yield since that time. Improvements in crop management aimed at improving yield and grain quality probably developed more slowly, but the rate of change has accelerated in recent decades. Many studies have shown that the contribution to increased yield from improved management has been about double that from breeding. Both processes have proceeded in parallel, although possibly at different rates in some periods, and positive interactions between breeding and management have been responsible for greater improvements than by either process alone in southern Australia (Anderson and Impiglia, 2002; Anderson *et al.*, 2005), as well as in similar areas of WANA (Harris *et al.*, 1991).

Several authors have shown the physiological basis for understanding the processes by which agronomic practices can affect the wheat crop in the field through increased water supply and its use efficiency (Passioura, 1977, 1983; Fischer, 1979; French and Schultz, 1984). However, many of these technologies are not widely implemented or are not seen as feasible by farmers. This can be attributed to a number of constraints, including technical, socio-economic and policy factors, but most importantly the lack of community participation in the development and implementation of improved technologies. The participation of farmer, researcher, extension agents in the testing, demonstration and dissemination of improved technology will lead to better awareness of the technology and its adoption by a large number of farmers. Of course, the degree and extent of adoption will remain dependent on the availability of crucial inputs, such as machinery, fertilizer and improved seed.

Yield Gap Analysis of Crops in SSA

The population in SSA is expected to grow at 3% a year and food production at less than 2%. The World Bank estimates that if the current trends in population growth and food production continue then Africa alone will have a food shortage of 250 million t by the year 2020. And poverty and the number of underfed children will grow accordingly (Pinstrup-Anderson, 1994). Currently more than 900 million people live in Africa and almost 200 million people are undernourished. More than 60% of malnourished Africans live in eastern Africa. On the other hand, West Africa as a whole has countered the trend in the rest of the continent, with its malnutrition falling dramatically in recent years (IAC Report, 2004).

In contrast to Asia, the agriculture in Africa is predominantly rainfed. The farming systems are diverse and livestock are an important part of the farming systems. It is envisaged that enhancing the productivity of maize, rice, sorghum, millet, wheat, cassava, yam, legumes, coffee and cocoa, which are the predominant components of the priority farming systems of Africa (IAC Report, 2004), would contribute greatly to reducing poverty and malnutrition in Africa. Here, we have presented the potential yields and yield gap of major crops (pearl millet, sorghum and maize) in the selected countries in West and central Africa and eastern and Southern Africa. The potential yields of the crops are based on simulation analysis or the review of literature on potential yields obtained at research stations or in farmers' fields under best farming practice for the crop or region.

West and central Africa: pearl millet, sorghum and maize

Pearl millet, sorghum and maize are of great importance for food security in the semi-arid tropical environments of West and central Africa. They are generally grown in mixtures with other crops, primarily legumes. Although these cereals do respond dramatically to modern technology, farm yields are generally low and progress has been limited. Most of the increase in production of these crops in the past 30 years has been due to increase in area under the crop and much less due to increase in yield (Table 6.11). In West Africa, since the period 1971–1975, the area under pearl millet, sorghum and maize increased by 57%, 86% and 200%, respectively, and the yields of these crops increased by 28%, 30% and 43%, respectively. In central Africa, although the

Table 6.11. Area, production and yield of pearl millet, sorghum and maize in West and central Africa[a].

Attribute	Millet		Sorghum		Maize	
	1971–1975	2001–2005	1971–1975	2001–2005	1971–1975	2001–2005
West Africa						
Area (million ha)	9.66	15.14	7.08	13.16	2.58	7.92
Production (million t)	5.79	11.62	4.90	11.79	2.20	9.72
Yield (kg/ha)	600	770	690	900	860	1230
Central Africa						
Area (million ha)	0.68	1.18	0.90	1.32	1.84	3.12
Production (million t)	0.42	0.66	0.59	1.15	1.46	2.91
Yield (kg/ha)	610	560	660	880	790	930

[a]Source: FAOSTAT (2006).

production of these crops is less as compared with that in West Africa, the trends in area and yield over time were similar. Future increase in production in Africa would require increase in productivity per unit of land area because of increasing limitations on land availability for annual crop production.

Yield gap of pearl millet in Niger

The pearl-millet-based cropping systems, as they are currently practised in the Sudano-Sahelian zone of West Africa, cannot meet the growing food needs of the region. They must, therefore, be intensified in a sustainable manner. Variable rainfall, coarse-textured soils, acidic pH, low organic matter, low water-holding capacity and nutrient deficiencies, particularly low phosphorus status of soils, are the limiting factors to increasing productivity of millet-based systems. Average yield of pearl millet in Niger is about 450 kg/ha considering all the rainfall environments where millet is grown. Subbarao *et al.* (2000) reported that in a long-term operational-scale study conducted from 1986 to 1996, comprising phosphorus fertilization, tillage and rotation with cowpea, the millet yields on average can be increased from 230 kg/ha with traditional management to 710 kg/ha with improved management, thus giving a yield gap of 480 kg/ha. On average, phosphorus fertilization alone improved the millet yield by 52%, while planting on ridges and phosphorus fertilization improved grain yield by nearly 135%. Combining ridge planting, phosphorus fertilization and rotation with sole cowpea resulted in a 200% increase in grain yield compared with the traditional system of production. These results show the potential to enhance the productivity of pearl millet with improved management in the region.

Potential yield and yield gap of sorghum

The mean potential yields of improved varieties and hybrids obtained in the experimental trials conducted at Samanko in Mali, Bengou in Niger and Bagouda in Nigeria and the corresponding farmers' average yields in these countries were used to quantify the yield gaps of sorghum in West Africa. The farmers' yields ranged from 730 to 1170 kg/ha with their current levels of management and varieties (Table 6.12). The potential yields over the five seasons ranged from 1420 to 2810 kg/ha at Samanko, 1360–4030 kg/ha at Bengou and 4420–5400 kg/ha at Bagouda, which gave a yield gap of 690–2080 kg/ha, 980–3650 kg/ha and 3250–4230 kg/ha for these locations, respectively. These yield gaps indicate the potential to enhance crop yields in these countries if improved agronomic management practices are adopted.

Potential yield and yield gap of maize

Maize is present in many African farming systems. Yield increases have, however, been modest overall, with greatest improvement in irrigated and commercial farming systems. Introduction of improved maize germplasm has had a significant impact on maize production in Africa. In favoured areas under farm conditions, hybrids have shown yield gains of at least 40% over local unimproved material (IAC Report, 2004). In dry areas, hybrids have provided at least 30% yield gain (Rohrbach, 1989; Lopez-Pereira and Morris, 1994). Especially notable is the rapid adoption of improved maize varieties in the savannah areas of western Africa, particularly Nigeria and important maize-growing regions in Ghana, Mali, Senegal and Zaire (Maredia *et al.*, 1998).

Apart from improved varieties, agronomic measures to improve soil fertility have led to

Table 6.12. Mean yield of 25 common entries in the International Sorghum Variety and Hybrid Adaptation Trials (ISVHAT), 1989–1993, at West African locations[a].

Location/country	Farmers' mean yield (kg/ha)	Range in improved yield (kg/ha)	Yield gap (kg/ha)
Samanko/Mali	730	1420–2810	690–2080
Bengou/Niger	380	1360–4030	980–3650
Bagouda/Nigeria	1170	4420–5400	3250–4230

[a]Source: ICRISAT (1989–1993).

dramatic yield improvements. In West Africa, the Sasakawa Global 2000 initiative has introduced a package of improved maize technologies to increase productivity. Farmers were given management training plots of 0.25 ha each and supplied with credit to purchase inputs (i.e. seeds of improved crop varieties, fertilizers and pesticides). While the average yields with improved management were 1.7 to 2.4 times the yields obtained under traditional management in the four countries, the variation in yields was also high (Table 6.13).

Eastern and Southern Africa: maize and sorghum

Maize and sorghum are the major crops grown in East Africa. Total productivity of these crops substantially increased in the region since the late 1970s (Table 6.14). Both increase in area and yield contributed to the increase in production. In Southern Africa, the area under maize and sorghum has decreased over the years. This decrease in area did not significantly influence the production of maize. The total production of maize rather increased because of increase in yield from 1810 to 2840 kg/ha since the late 1970s (Table 6.14). In case of sorghum, total production of sorghum decreased in spite of an increase in yield of sorghum from 1270 to 1930 kg/ha.

Yield gap of maize in Kenya

Trends in maize production were analysed using the production data of Machakos and Makueni districts in Kenya. Machakos and Makueni districts are in the Eastern Province of Kenya and lie between latitudes 37° 00′ E and 38° 30′ E and longitudes 1° S and 3° 15′ S (Fig. 6.25). The two districts cover an area of 1.33 million ha, of which 1.13 million ha is agricultural land including ranches. Actual district crop production statistics for the period 1970–2002 were collected from published (Mbogoh, 1991) and unpublished district annual reports from the Ministry of Agriculture and District Agricultural Officers'

Table 6.13. Yield increase in maize due to the adoption of a technology package comprising improved varieties, fertilizers and pesticides[a].

Country	Period	Traditional yield (kg/ha)	Average improved yield (kg/ha)	Range in improved yield (kg/ha)
Burkina Faso	1996–2000	1120	2700	2200–3500
Ghana	1997–1999	1480	3600	3300–4800
Guinea	1999–2000	1450	2800	2600–3000
Mali	1998–2000	1610	2800	1200–6400

[a]Source: IAC Report (2004).

Table 6.14. Area, production and yield of maize and sorghum in eastern and Southern Africa during the period 1971–1975 to 2001–2005[a].

	Maize		Sorghum	
Attributes	1971–1975	2001–2005	1971–1975	2001–2005
Eastern Africa				
Area (million ha)	7.61	11.00	2.98	4.01
Production (million t)	8.93	15.19	2.40	4.00
Yield (kg/ha)	1170	1380	800	1000
Southern Africa				
Area (million ha)	4.80	3.51	0.42	0.16
Production (million t)	8.67	9.97	0.53	0.30
Yield (kg/ha)	1810	2840	1270	1930

[a]Source: FAOSTAT (2006).

Fig. 6.25. Map of Kenya showing the location of Machakos and Makueni districts.

offices. Long-term climate data for Katumani were obtained from Katumani research station while the experimental station yields were taken from a long-term trial conducted at Katumani research station over 19 crop seasons between 1990 and 1999 (Okwach and Simiyu, 1999).

The area under maize in Machako and Makueni districts of Kenya nearly doubled from 128,000 ha during 1970–1974 to 229,000 ha during 1998–2002. Much of this increase took place during 1985–1995. Since 1995, the area under maize remained constant, mainly due to non-availability of land suitable for maize production. Most of the maize in the districts is grown under rainfed conditions. Productivity of maize during 1970–2002 has varied from 210 to 1390 kg/ha with a coefficient of variation (CV) of 43%, which is primarily attributed to the variability in seasonal rainfall. The CVs for the short (October–December) and long (March–May) season rainfall for the corresponding period are 44% and 46%. However, since 1990 a strong declining trend in maize yields has been observed, which cannot be explained by the variation in rainfall alone. Mean yield recorded during 1998–2002 was only 400 kg/ha, which is nearly 50% of what farmers were harvesting in the early 1970s. A similar declining trend in maize yields during the same period was also observed at the national level, arising primarily from the decline in yields in the districts having a high percentage of area under arid and semi-arid lands (ASAL). Although it is not clear what factors are contributing to this decline, it is assumed that declining soil fertility and extension of agriculture into more marginal areas are the two major contributing factors.

Considering the strong influence of climate on the productivity of maize, the yield trends in above-normal, normal and below-normal rainfall seasons were analysed. Seasons with rainfall up to 250 mm were classified as below normal, with 250–349 mm as normal and those with more than 350 mm as above normal using the criteria derived by Stewart and Faught (1984).

However, we used a rainfall limit of 250 mm to classify the season as below normal instead of 220 mm used by Stewart and Faught (1984). Crop yields based on the district crop production data were found to be higher during the years when both short rainy and long rainy seasons were normal or during the years where the short rainy season is normal and the long rainy season is above normal (Fig. 6.26). Maize yields showed no difference when both seasons were either below normal or above normal, though the rainfall during above-normal years was nearly double that received during below-normal years (Fig. 6.27). This is attributed to the low-input management strategies adopted by the farmers. While analysing the production profile of the district between 1960 and 1990, Tiffen *et al.* (1994) observed that farmers pursue strategies that successfully maintain yields in somewhat below mean years but do not seem to be able to take advantage of very good rainfall. Additionally, during high rainfall seasons, the crop is expected to experience higher nitrogen deficiency as leaching removes small quantities of available nitrogen from the root zone.

PRODUCTIVITY AT FARM LEVEL The results of a survey conducted at two locations, Mwala in Machakos district and Makindu in Makueni district, during the 2003–2004 short rainy season, covering 54 households, indicated that the crop yields varied with season and ranged from complete crop failure to four to five bags per acre in good seasons. Mean yields expected during the three different types of seasons at Mwala and Makindu are summarized in Table 6.15. At Makindu farmers expected lower yields compared with those at Mwala, which can be explained by lower mean annual rainfall at Makindu (about 600 mm) compared with Mwala (about 700 mm). During the 2004 short rainy season, we recorded the yields obtained by farmers at Mwala to verify the farmers' assessment. The 2004 short rainy season was

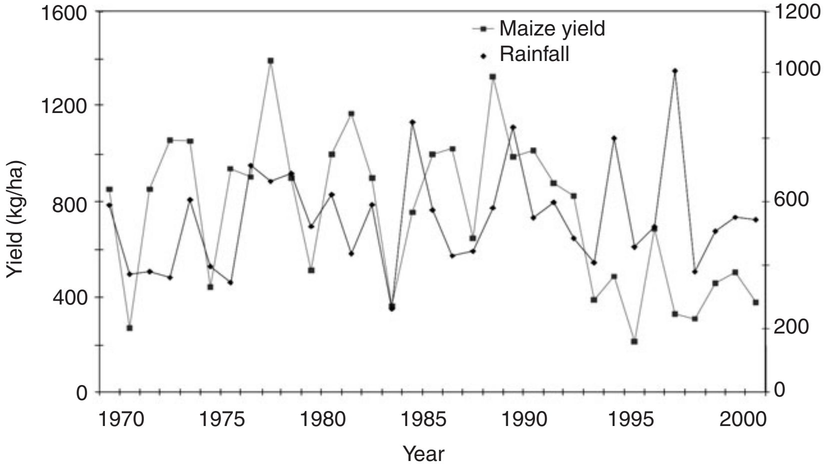


Fig. 6.26. Rainfall and maize yields in Machakos district (data from 1992 onwards are total for Machakos and Makueni districts).

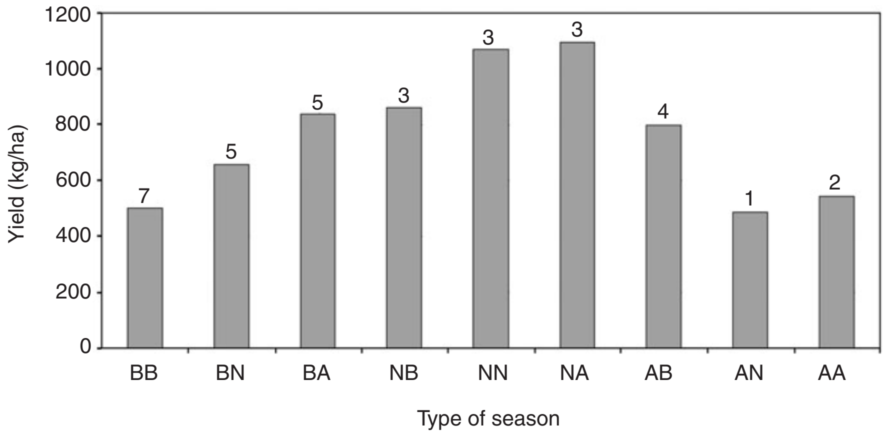


Fig. 6.27. Productivity of maize during below-normal (B <250 mm), normal (N = 250–350 mm) and above-normal (A >350 mm) seasons (figures on the bars indicate the number of years under that category).

Table 6.15. Yields expected by farmers at Makindu and Mwala in different seasons.

		Maize yield (kg/ha)	
Type of season	Rainfall (mm)	Makindu (Makueni)	Mwala (Machakos)
Below normal	<250	115	222
Normal	250–350	335	561
Above normal	>350	748	1297

considered normal with about 250 mm rainfall. Yields recorded varied from 200 to 2200 kg/ha with an average of 1020 kg/ha, which corresponds well with what farmers had indicated to achieve in above-normal season.

RESEARCH STATION POTENTIAL YIELDS AND YIELD GAPS

Data collected from a long-term trial conducted at Katumani research station over 19 seasons were analysed to assess the maize yields achieved on the research station. The low-input system comprised Katumani maize with a plant population of 22,000 plants/ha with no mulch and fertilizer; while the high-input system used the same variety with 53,000 plants/ha and all the stubbles from the previous season as mulch and fertilized with 100 kg nitrogen per ha and 10 kg phosphorus per ha. Of the total 19 seasons, eight seasons were below normal, five were normal and six were above normal.

Under low-input management, highest maize yields were recorded during normal seasons while yields during above-normal years were lower (Fig. 6.28). Maize yields during below-normal years were about 40% of those recorded during normal years. Yields obtained under high-input management clearly indicated the possibility of enhancing the yields by two- to threefold. Although there is possibility of increasing the yields in the below-normal seasons by about 1 t under high-input management, the risk involved in making those investments is very high owing to the possibility of crop failure. The potential to increase yields is much higher during normal and above-normal years with little risk of losing on investments compared with below-normal years. The crop never failed in the seasons that received more than 250 mm rainfall.

SIMULATED RAINFED POTENTIAL YIELDS AND YIELD GAPS

Crop yields were simulated for 93 seasons starting in 1957 up to 2003 using a maize simulation model available in APSIM software and long-term weather data for Katumani (Table 6.16). The model had been earlier calibrated and validated for the Katumani location by Okwach and

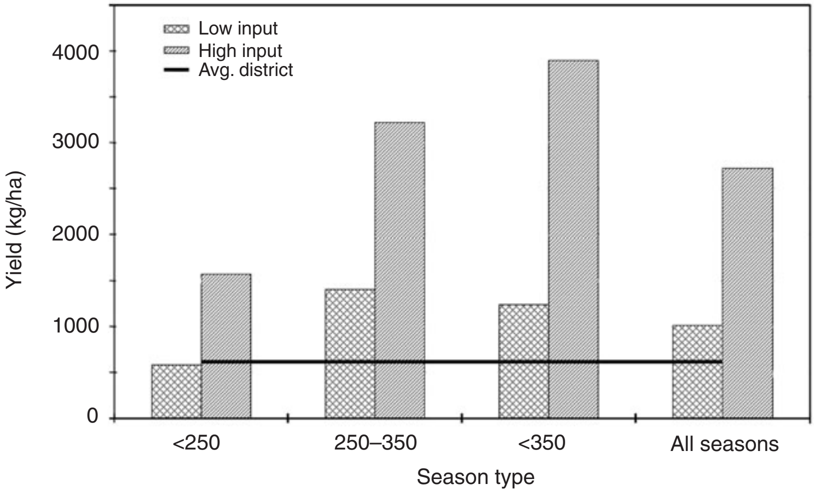


Fig. 6.28. Maize yields under low- and high-input systems in various season types (data from the long-term trial).

Table 6.16. Experimental and simulated yields of maize in different seasons under low- and high-input management.

Management	Below normal (<250 mm)	Normal (250–350 mm)	Above normal (>350 mm)
Experimental yields (kg/ha)			
Low-input management[a]	580	1400	1240
High-input management[b]	1570	3220	3890
Yield gap	990	1820	2580
Simulated rainfed yields (kg/ha)			
Low-input management[a]	310	470	450
High-input management[b]	1560[c]	3310	4220
Yield gap	1250	2840	3770
Simulated potential yields (kg/ha) – water and nitrogen non-limiting			
Short rainy season	7680	7280	7360
Long rainy season	4990	6060	5280

[a] 22,000 plants/ha with no fertilizer; [b] 53,000 plants/ha, stubble mulch, 100 kg N per ha + 10 kg P per ha; [c] 22,000 plants/ha with 50 kg N per ha.

Simiyu (1999) and Okwach (2002). The results showed that complete crop failure occurred during nine seasons, of which five are short rainy seasons and four long rainy seasons. Simulated yields for low-input management were lower than those observed in the trial. This was mainly due to the gradual decline in yields due to fertility depletion. A similar trend would have been observed if the trial had continued for a similar number of seasons. The mean simulated yields under different management options were very similar to the yields obtained in the trial under high-input management.

The maximum possible productivity of maize that can be achieved in Machakos in water and nutrient non-limiting situations was also assessed using the maize model. For this simulation, we used the model option of non-limiting nitrogen and application of irrigation whenever the available moisture fell below 75% of maximum available capacity between sowing and harvest. The maize variety used was Katumani, which is widely adopted in the district. The highest mean yield was obtained with a population of 90,000 plants/ha. Maize yields were found to be higher during short rainy seasons compared with long rainy seasons. The mean yield of all short rainy seasons was 7470 kg/ha, which was 2210 kg/ha higher than the mean yield of all long rainy seasons. While the highest yields during short rains were recorded in the seasons with <250 mm rainfall, mean yields were found to be higher during normal years in the long rainy seasons. This is perhaps one reason why farmers in the region believe that short rainy seasons are more dependable, with higher yields than long rainy seasons.

Yield gap of sorghum in Kenya and Zimbabwe

The mean potential yields of improved varieties and hybrids obtained in the experimental trials conducted at Kiboko in Kenya and Matopos in Zimbabwe and the corresponding farmers' average yields in these countries were used to quantify the yield gaps of sorghum. The farmers' yields ranged from 470 to 860 kg/ha with their current levels of management and varieties (Table 6.17). The potential yields with improved variety and improved management over the five seasons ranged from 1760 to 5240 kg/ha at Kiboko and from 3420 to 5530 kg/ha at Matopos, which gave a yield gap of 900–4380 kg/ha and 2950–5060 kg/ha for these locations, respectively. These yield gaps indicate that the crop yields in these countries can be substantially increased if improved practices are adopted.

Constraints and opportunities for bridging the yield gaps in SSA

In general, there are three major challenges in SSA with respect to soil and water resources for agriculture. First is the climatic variability, which leads to unreliability in the soil moisture available for plant growth, even in high rainfall areas. It is because of this variability that the sub-region has failed to convert its relatively larger gross water resources into meaningful economic assets. Indeed, the level of poverty and frequency of drought-induced food deficits in the region are in sharp contrast to the abundant water endowment in the form of direct rainfall. Second, with inherently low soil fertility of most of the soils in SSA, coupled with very low use of soil fertility-enhancing inputs, many agricultural lands are experiencing a high rate of nutrient depletion, leading to rapidly decreasing productivity of land and water resources. There is a need to develop more integrated management practices. Third, the subsistence nature of smallholder farming in SSA limits investments in the development and sustainable management of land and water resources. These constraints need to be overcome through national and international support to enhance food production in SSA.

Summary and Conclusions

The world population is expected to reach 8.0 billion by 2025. Most of this increase in population is expected to occur in less-developed countries in South and South-east Asia, WANA region and SSA, where most of the poor live. By 2025, while South Asia will have the maximum absolute food demand in the world, SSA will have to more than double its food production from the current levels to meet the food needs of a burgeoning population. About a 55–68% increase in food demand is also expected in South-east Asia and the WANA region. Many countries in the region will have to import food to make up the deficits. With the exception of some countries in SSA, most of the

Table 6.17. Mean yield of 25 common entries in the International Sorghum Variety and Hybrid Adaptation Trials (ISVHAT), 1989–1993, in Kenya and Zimbabwe[a].

Location/country	Farmers' mean yield (kg/ha)	Range in improved yield (kg/ha)	Yield gap (kg/ha)
Kiboko/Kenya	860	1760–5240	900–4380
Matopos/Zimbabwe	470	3420–5530	2950–5060

[a]Source: ICRISAT (1989–1993).

increase in food production must occur as a result of productivity increase per unit of land area rather than area expansion because of increasing land degradation and competition for land for other uses.

Analysis of potential yields and yield gaps of crops at selected locations in South and South-east Asia, WANA region and SSA showed that the actual yields of food and other crops obtained by the farmers are much below the potential yields that can be obtained with improved management. The analysis also showed that, although there are regional differences in the potential of different agroecologies of the developing world, the crop yields can be at least doubled from their current levels by the promotion and adoption of existing 'on-the-shelf' technologies available with the national and international research institutes. It is clear that the full potential of rainfed farming has not been exploited as yet. It is possible to increase food production substantially through crop yield improvements in all the countries in South and South-east Asia, the WANA region and in SSA by proper management and use of natural resource and implementation of improved crop management practices. The IGNRM approach that incorporates soil and water conservation, water harvesting for supplemental irrigation, integrated nutrient management to achieve balanced nutrition of crops, growing of high-yielding improved varieties of crops and integrated pest and disease management needs to be adopted for enhancing crop yields and for efficient management and use of natural resources. The governments need to provide more suitable policy environments and institutional support to promote greater adoption of new and improved technologies to benefit the poor farmers of rainfed areas and to meet the challenge of the greater food needs of the future.

References

Aggarwal, P.K., Banerjee, B., Daryaei, M.G., Bhatia, A., Bala, A., Rani, S., Chander, S., Pathak, H. and Kalra, N. (2006) InfoCrop: a dynamic simulation model for the assessment of crop yields, losses due to pests and environmental impact of agroecosystems in tropical environments. II. Model performance. *Agricultural Systems* 89, 47–67.

Anderson, W.K. and Impiglia, A. (2002) *Management of Dryland Wheat*. In: Curtis, B.C., Rajaram, S. and Gomez Macpherson, H. (eds) Food and Agricultural Organization of the United Nations (FAO), Rome, Italy, pp. 407–432.

Anderson, W.K., Hamza, M.A., Sharma, D.L., Antuono, M.F.D., Hoyle, F.C., Hill, N., Shackley, B.J., Amjad, M. and Zaicou-Kunesch, C. (2005) The role of management in yield improvement of the wheat crop – a review with special emphasis on Western Australia. *Australian Journal of Agricultural Research* 56, 1137–1149.

Avci, M. (2005) New decision support tool: farmer survey for optimizing soil water use in the Anatolian plateau. In: *Management for Improved Water Use Efficiency in the Dry Areas of Africa and West Asia*. Proceedings of a workshop organized by the Optimizing Soil Water Use (OWSU) Consortium, 22–26 April 2002, Ankara, Turkey, pp. 101–109.

Avci, M., Guler, M., Pala, M., Durutan, N., Karaca, M. and Eyuboglu, H. (1987) The effects of the different components of package of cultural practices on wheat yield under central Anatolian conditions of Turkey. In: *Cereal Symposium*. Faculty of Agriculture, 6–9 Oct 1987, Bursa, Turkey (in Turkish), TUBITAK, U.U, pp. 147–157.

Bhalla, G.S., Hazell, P. and Err, J. (1999) Prospects for India's cereal supply and demand for 2020. Food, Agriculture and the Environment. Discussion Paper 29. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Bhatia, V.S., Singh, P., Wani, S.P., Kesava Rao, A.V.R. and Srinivas, K. (2006) Yield gap analysis of soybean, groundnut, pigeonpea and chickpea in India using simulation modelling. *Global Theme on Agroecosystems Report No. 31*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Borlaug, N.E. (2001) Feeding the world in the 21st century: the role of agricultural science and technology. Speech given at Tuskegge University, April 2001, pp. 1–9. Accessible at http://www.agbioworld.org/biotech-info/topics/borlaug/ borlaugspeech.htm

Bounejmate, M., Christiansen, S., Ryan, J., Pala, M. and Shomo, F. (2002) Common vetch to reverse long-term land degradation and alleviate the feed deficits in Syria. In: Ryan, J. (ed.) *Desert and Dryland Development: Challenges and Potential in New Millennium*. Proceedings of the Sixth International Conference on the Development of Drylands, 22–29 Aug 1999, Cairo, Egypt. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, pp. 253–260.

Chinh, N.T., Tam, H.M., Long, T.D. and Thang, N.V. (2000) New technology for groundnut growing in Vietnam. In: *Vietnam Agricultural Science Institute Annual Report 2000*. Agricultural Publisher, VASI, Vietnam, pp. 149–155.

Chuc, N.T., Piara Singh, Srinivas, K., Ramakrishna, A., Chinh, N.T., Thang, N.V., Wani, S.P. and Long, T.D. (2005) Yield gap analysis of major rainfed crops of northern Vietnam using simulation modelling. *Global Theme on Agroecosystems Report No. 26*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Cooper, P.J.M., Gregory, P.J., Tully, D. and Harris, H.C. (1987) Improving water-use efficiency of annual crops in the rainfed farming systems of West Asia – North Africa. *Experimental Agriculture* 23, 113–158.

Durutan, N., Pala, M., Karaca, M. and Yesilsoy, M.S. (1989) Soil management, water conservation and crop production in the dryland regions of Turkey. In: Whitman, C.E., Parr, J.F., Papendick, R.I. and Meyer, R.E. (eds) *Proceedings of Soil, Water and Crop/Livestock Management Systems for Rainfed Agriculture in the Near East Region*, 18–23 January 1986, International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria. Amman, Jordan, pp. 60–77.

FAO (2004) International year of rice. Fact Sheet No. 5. (www.rice2004.org).

FAOSTAT (2002, 2004 and 2006) Accessible at http://www.fao.org/

Fischer, R.A. (1979) Growth and water limitation to dryland wheat yield in Australia: a physiological framework. *Journal of the Australian Institute of Agricultural Science* 45, 83–94.

French, R.J. and Schultz, J.E. (1984) Water use efficiency of wheat in a Mediterranean-type environment. II. Some limitations to efficiency. *Australian Journal of Agricultural Research* 35, 765–775.

General Statistics of Vietnam (2007) Accessible at http://www.gso.gov.vn (last accessed 31 October 2007).

GOI (Government of India) (2006) *Agricultural Statistics at a Glance*. Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, New Delhi, India. Accessible at http://decnet.nic.in/eands/agstat06–07.htm

Harris, H.C. (1995) Long-term trials on soil and crop management at ICARDA. Soil management: experimental basis for sustainability and environmental quality. *Advances in Soil Science* 19, 447–469.

Harris, H.C., Cooper, P.J.M. and Pala, M. (eds) (1991) *Soil and Crop Management for Improved Water Use Efficiency in Rainfed Areas*. Proceedings of an International Workshop sponsored by MAFRA/ICARDA/CIMMYT, 15–19 May 1989, Ankara, Turkey. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Hoogenboom, G., Wilkens, P.W., Thornton, P.K., Jones, J.W., Hunt, L.A. and Imamura, D.T. (1999) Decision support system for agrotechnology transfer v3.5. In: Hoogenboom, G., Wilkens, P.W. and Tsuji, G.Y. (eds) *DSSAT Version 3. Vol. 4.* University of Hawaii, Honolulu, USA, pp. 1–36.

IAC Report (2004) Realizing the promise and potential of African Agriculture. Accessible at http://www.interacademycouncil.net/CMS/Reports/AfricanAgriculture.aspx

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (1989 to 1993) *ICRISAT Cereals Program Reports. International Sorghum Variety and Hybrid Adaptation Trials, 1989 to 1993*. ICRISAT, Patancheru 502 324, Andhra Pradesh, India.

Kanwar, J.S. (2000) Soil and water resource management for sustainable agriculture imperatives for India. In: International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century, invited papers. 14–18 February 2000, New Delhi. Water Technology Centre and Indian Agricultural Research Institute, New Delhi 110 012, India, pp. 4–6.

Karaca, M., Durutan, N., Guler, M., Pala, M. and Unver, I. (1989) The effect of fallow tillage systems on wheat yields in Central Anatolia of Turkey. In: Unger, P.W., Sneed, T.V., Jordan, W.J. and Jensen, R. (eds) *Challenges in Dryland Agriculture – a Global Perspective*. Proceedings of the International Conference on Dryland Farming, 15–19 August 1988. Amarillo/Bushland, Texas, USA, pp. 131–133.

Kassam, A.H. (1988) Some agroclimatic characteristics of high-elevation areas in North Africa, West Asia, and South-east Asia. In: Srivastava, J.P., Saxena, M.C., Varma, S. and Tahir, M. (eds) *Winter Cereals and Food Legumes in Mountainous Areas*. Proceedings of an International Symposium, 10–16 July 1988, Ankara, Turkey. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, pp. 1–32.

Kumar, P. (1998) Food demand and supply projections for India. Agricultural Economics Policy Paper 98–01. Indian Agricultural Research Institute (IARI), New Delhi, India.

Land Development Department (2000) *Yield Gap Analysis of Three Main Watersheds in the Northeastern Thailand.* Land Development Department, Thailand.

Lopez-Pereira, M.A. and Morris, M.L. (1994) *Impacts of International Maize Breeding Research in the Developing World, 1966–1990.* International Maize and Wheat Improvement Center (CIMMYT), Mexico.

Maredia, M., Byerlee, D. and Pee, P. (1998) Impacts of food crop improvement research in Africa. Special Program for African Agricultural Research (SPAAR) Occasional Papers Series 1. Africa Region. World Bank, Washington, DC.

Mbogoh, S.G. (1991) Crop production. In: Tiffen, M. (ed.) Environmental change and dryland management in Machakos district, Kenya 1930–90: production profile. ODI Working Paper 55. Overseas Development Institute (ODI), London, UK.

McCowen, R.L., Hammer, G.L., Hargreaves, J.N.G., Halzworth, D.P. and Freebairn, D.M.C. (1995) APSIM: a novel software system for model development, model testing and simulation in agricultural systems research. *Agricultural Systems* 50, 255–271.

Okwach, G.E. (2002) Developing an appropriate tool for managing run-off, erosion, and crop production in semi-arid eastern Kenya: a case for APSIM model. CARMASAK Technical Report No. 3. Kenya Agricultural Research Institute, Kenya.

Okwach, G.E. and Simiyu, C.S. (1999) Effects of land management on run-off, erosion, and crop production in a semi-arid area of Kenya. *East African Agricultural and Forestry Journal,* Special Edition 65(2), 125–142.

Osman, A.E., Ibrahim, M.H. and Jones, M.A. (eds) (1990) *The Role of Legumes in the Farming Systems of the Mediterranean Areas.* Proceedings of a workshop on the role of legumes in the farming systems of the Mediterranean areas, 20–24 June 1988, UNDP/ICARDA, Tunis. Development in Plant and Soil Sciences 38. Kluwer Academic Publishers, the Netherlands.

Oweis, T., Pala, M. and Ryan, J. (1998) Stabilizing rainfed wheat yields with supplemental irrigation and nitrogen in a Mediterranean-type climate. *Agronomy Journal* 90 (5), 672–681.

Oweis, T., Pala, M. and Ryan, J. (1999) Management alternatives for improved durum wheat production under supplemental irrigation in Syria. *European Journal of Agronomy* 11, 255–266.

Oweis, T., Zhang, H. and Pala, M. (2000) Water use efficiency of rainfed and irrigated bread wheat in a Mediterranean environment. *Agronomy Journal* 92, 231–238.

Pala, M. (2005) Agronomic management for improved water use efficiency in the dry areas of West Asia and North Africa. In: Pala, M., Beukes, D.J., Dimes, J.P. and Myers, R.J.K. (eds) *Proceedings of a Workshop on Management for Improved Water Use Efficiency in the Dry Areas of Africa and West Asia* organized by Optimizing Soil Water Use (OSWU) Consortium, 22–26 April 2002, Ankara, Turkey. International Center for Agriculture Research in the Dry Areas (ICARDA), Aleppo, Syria and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India, pp. 185–200.

Pala, M., Stockle, C.S. and Harris, H.C. (1996) Simulation of durum wheat (*Triticum turgidum* ssp. durum) growth under different water and nitrogen regimes in a Mediterranean environment using CropSyst. *Agricultural Systems* 51(2), 147–163.

Pala, M., Harris, H., Ryan, J., Makboul, R. and Dozom, S. (2000) Tillage systems and stubble management in a Mediterranean-type environment in relation to crop yield and soil moisture. *Experimental Agriculture* 36, 223–242.

Pala, M., Ryan, J., Mazid, A., Abdallah, O. and Nachit, M. (2004) Wheat farming in Syria: an approach to economic transformation and sustainability. *Renewable Agriculture and Food Systems* 19 (1), 30–34.

Passioura, J.B. (1977) Grain yield, harvest index, and water use of wheat. *Journal of the Australian Institute of Agricultural Science* 43, 117–120.

Passioura, J.B. (1983) Roots and drought resistance. *Agricultural Water Management* 7, 265–280.

Piara Singh, Vijaya, D., Chinh, N.T., Pongkanjana, A., Prasad, K.S., Srinivas, K. and Wani, S.P. (2001) Potential productivity and yield gap of selected crops in the rainfed regions of India, Thailand and Vietnam. Natural Resource Management Program Report No. 5. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Pinstrup-Andersen, P. (1994) World food trends and future food security: meeting tomorrow's food needs without exploiting the environment. Accessible at www.ifpri.org/pubs/fps/fps18.htm.

Rego, T.J., Sahrawat, K.L., Wani, S.P. and Pardhasaradhi, G. (2007) Widespread deficiencies of sulfur, boron, and zinc in Indian semi-arid tropical soils: on-farm crop responses. *Journal of Plant Nutrition* 30(10), 1569–1583.

Rohrbach, D. (1989) The economics of smallholder maize production in Zimbabwe: implications for food security. MSU International Development Paper No. 11. Department of Agricultural Economics, Michigan State University, USA.

Rosegrant, M.W., Ximing, C. and Cline, S.A. (2002) *World Water and Food to 2025*: *Dealing with Scarcity*. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

SCBS (Syrian Central Bureau of Statistics) (1998) *Statistical Abstract*. SCBS, Damascus, Syria.

Singh, H.P., Venkateswarlu, B., Vittal, K.P.R. and Ramachandran, K. (2000) Management of rainfed agro-ecosystem. *Proceedings of the International Conference on Managing Natural Resources for Sustainable Agricultural Production in the 21st Century*. 14–18 February, New Delhi, India. Secretary General, International Conference on Managing Natural Resources for Sustainable Agriculture Production in the 21st Century, pp. 669–774.

Singh, R.P. and Venkateswarlu, J. (1985) Role of All India Coordinated Research Project for dryland agriculture in research and development. *Fertiliser News* 39(4), 43.

Stewart, J.I. and Faught, W.A. (1984) Response farming of maize and beans at Katumani, Machakos district, Kenya: recommendations, yield expectations, and economic benefits. *East African Agricultural and Forestry Journal* 44, 29–51.

Stockle, C.O., Martin, S. and Campbell, G.S. (1994) CropSyst, a cropping systems model: water/nitrogen budgets and crop yield. *Agricultural Systems* 46, 335–359.

Subbarao, G.V., Renard, C.R., Payne, W.A. and Bationo, A.B. (2000) Long-term effects of tillage, P fertilization and crop rotation on pearl millet/cowpea productivity in West Africa. *Experimental Agriculture* 36, 243–264.

Tiffen, M., Mortimore, M. and Gichuki, F. (1994) *More People, Less Erosion. Environmental Recovery in Kenya*. John Wiley and Sons, Chichester, UK.

United Nations (2006) Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: the 2006 Revision and World Urbanization Prospects: the 2005 Revision, http://esa.un.org/unpp (accessed 29 October, 2007).

van Duivenbooden, N., Pala, M., Studer, C., Bielders, C.L. and Beukes, D.J. (2000) Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *Netherland Journal of Agricultural Science* 48, 213–236.

Venkateswarlu, J. (1987) Efficient resource management systems for drylands of India. *Advances in Soil Science* 7, 165–221.

WANADIN (2000) West Asia and North Africa Durum Improvement Network Project Final Report. IFAD/ICARDA, Aleppo, Syria.

Wangkahart, T., Toomsan, B., Pathak, P. and Wani, S.P. (2005) Integrated watershed management for land degradation and improving agricultural productivity in north-east Thailand. In: Sharma, BR., Samra, J.S., Scott, C.A. and Wani, S.P. (eds) *Watershed Management Challenges: Improving Productivity, Resources and Livelihoods*. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 314–326.

Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, T.J. (eds) (2003a) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia.* Proceedings of the ADB-ICRISAT-IWMI annual project review and planning meeting, 10–14 December 2001, Hanoi, Vietnam. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003b) Efficient management of rainwater for increased productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture. Limits and Opportunities for Improvement.* CAB International, Wallingford, UK, pp. 199–215.

Zhang, H., Oweis, T.Y., Garabed, S. and Pala, M. (1998) Water use efficiency and transpiration efficiency of wheat under rain-fed conditions and supplemental irrigation in a Mediterranean-type environment. *Plant and Soil* 201, 295–305.

7 Can Rainfed Agriculture Feed the World? An Assessment of Potentials and Risk

C. de Fraiture,[1]* L. Karlberg[2] and J. Rockström[2]**
[1] *International Water Management Institute (IWMI), PO Box 2075, Colombo, Sri Lanka;*
[2] *Stockholm Environment Institute (SEI), Stockholm, Sweden;*
*emails: *c.fraiture@cgiar.org; **johan.rockstrom@sei.se*

Introduction

Agriculture is practised on 12% of the total land area, hosting around 42% of the global population (FAOSTAT, 2000, 2003). Most of this area, around 80%, is under rainfed agriculture (FAOSTAT, 2005), which plays a predominant role in global food supply and water demand for food. There are large regional variations. While the majority of the agricultural land in sub-Saharan Africa is rainfed, most of the agricultural production in South Asia comes from irrigated agriculture.

Approximately 7000 km^3 of water is used annually in crop production (Rockström *et al.*, 1999; de Fraiture *et al.*, 2007; Lundqvist *et al.*, 2007), corresponding to 3000 l/person/day. The majority of this water originates from the green water resource (78%), while the remaining 22% is met by irrigation (de Fraiture *et al.*, 2007). Today, more than 1.2 billion people live in water-scarce river basins (Molden *et al.*, 2007a), and recent forecasts warn of aggravated global water scarcity unless water resources management is changed (Alcamo *et al.*, 1997; Seckler *et al.*, 1998; Seckler and Amarasinghe, 2000; Shiklomanov, 2000; Rosegrant *et al.*, 2002a, 2006; Bruinsma, 2003; Falkenmark and Rockström, 2004; SEI, 2005).

With rising incomes and growing population, food demand is expected to increase by 70–90% (de Fraiture *et al.*, 2007). Food habits change with increasing GDP (gross domestic product) to include more nutritious and more diversified diets, resulting in a shift in consumption patterns among cereal crops and away from cereals towards livestock products and high-value crops such as fruits, vegetables, sugar and edible oils; however, regional and cultural differences are large. Bioenergy is expected to add to the demand of agricultural produce, in order to increase the supply of transport fuels (i.e. biofuels) as a response to rising energy prices, geopolitics and concerns over greenhouse gas emissions. Future water requirements for bioenergy production have been estimated to range from 4000 to 12,000 km^3/year (Lundqvist *et al.*, 2007). The large uncertainty is a reflection of difficulties in estimating water productivity, which, for example, depends on how much of the biomass can be used for bioenergy production.

One of the options to respond to increased pressure on water resources is to boost low productivity through investments in water management in rainfed agriculture. There are several compelling environmental, social and economic reasons to do so. Yet, with rapidly growing and changing agricultural demand and increased climate variability due to climate change, the potential of rainfed agriculture to meet future food demand is subject to debate.

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

In this chapter, we examine how far rainfed agricultural production can meet future food demands in 2050. Two different productivity scenarios are compared, one pessimistic and one optimistic, using the WATERSIM model and estimates of potential yields for different agroecological zones. Moreover, the implications of these scenarios on risk minimization are illustrated.

Reasons to Upgrade Rainfed Agriculture

Large scope for poverty alleviation

Agriculture plays a key role in economic development (World Bank, 2005) and poverty reduction (Irz and Roe, 2000). For example, it has been shown that every 1% increase in agricultural yields translates into a 0.6–1.2% decrease in the absolute poor (Thirtle *et al.*, 2002). In sub-Saharan Africa the majority of the poor make their living from agriculture. In this region, agriculture, which is predominantly rainfed, employs 70% of the population and accounts for 35% of GDP (World Bank, 2000). Thus, agriculture is the engine of overall economic growth and, consequently, of broad-based poverty reduction (Johnston and Mellor, 1961; World Bank, 1982; Timmer, 1988; Abdulai and Hazell, 1995; IFAD, 2001; DFID, 2002; Koning, 2002, Wani *et al.*, 2008), and there are therefore strong reasons to believe that investments in low-yielding rainfed agriculture could have large impacts on poverty reduction.

Low investment costs

With rising concern over the high cost of expanding large-scale irrigation and environmental impacts of large dams, the role of upgrading rainfed agriculture is gaining increased attention. For example, irrigated cereal production in sub-Saharan Africa, characterized by high marketing and transportation costs and limited marketing opportunities, might not be able to compete with subsidized food imports from the USA and Europe. In addition, the institutional infrastructure and experience required for irrigation operation, maintenance and management are lacking. In a review of 311 case studies on watershed programmes in India focusing on rainwater management, the cost–benefit ratio was found to be 1:2.14, which can be considered relatively high (Joshi *et al.*, 2005). Micro-credit schemes for water management investments in rainfed agriculture have been suggested as a core strategy for enabling small-scale farmers to invest in water management in rainfed agriculture (Wani *et al.*, 2008).

Environmental concerns related to large-scale irrigation

Diversion of water from rivers and lakes for agricultural purposes often adversely affects aquatic ecosystems (e.g. Richter *et al.*, 1997; Revenga *et al.*, 2000; WCD, 2000; Bunn and Arthington, 2002; MEA, 2005a,b). Negative impacts include channel erosion, declines in biodiversity, introduction of invasive alien species, reduction of water quality, habitat fragmentation and reduced protection of flood plains and other inland and coastal fisheries. On the field scale, there are two main undesirable impacts of irrigation: salinization and waterlogging (Tanji, 1990). In 1994, it was estimated that around 10% of the earth's total land surface is covered with saline soils (Szabolcs, 1994). The Goulburn Broken Catchment in Australia is one example of a region presently suffering from rising water tables due to irrigation and the removal of natural vegetation (trees), and associated problems with the threat of waterlogging and salinization, which has rendered the region extremely susceptible to chocks (Anderies *et al.*, 2005). Large-scale irrigation carries environmental risks and associated costs, which works in favour of investments in rainfed agriculture.

Large yield gaps – high potential

In developing countries, rainfed grain yields are on average 1.5 t/ha, and increases in production have originated mainly from land expansion (Rosegrant *et al.*, 2002b). On the other hand, in temperate regions rainfed agriculture has some of the world's highest yields, and even in tropical regions, agricultural yields in commercial rainfed agriculture exceed 5–6 t/ha (Rockström and Falkenmark, 2000; Wani *et al.*, 2003a,b). In semi-arid regions in Africa and Asia, farmers' yields are two to four times lower than achievable yields for major rainfed crops (Rockström *et al.*, 2007, Wani *et al.*, Chapter 1, this volume). Such large yield gaps indicate a high potential for investments in rainfed agriculture.

Risk minimization – opening up for further investments

Low profitability of agriculture and high risks discourage farmers from investing in land and water management. In semi-arid and dry subhumid agroecosystems, dry spells occur almost every rainy season (Barron *et al.*, 2003). No overall estimates on losses because of drought and short dry spells are available, but yield figures show an enormous year to year variation. However, meteorological droughts, i.e. periods of inadequate rainfall to grow a crop, occur only once or twice every 10 years. Therefore, there is a large potential for investments in water management to bridge dry spells and secure harvests in most years. Furthermore, such a risk minimization is likely to have positive spin-off effects on further investments in yield-increasing inputs such as fertilizers.

Assessing the Potential for Rainfed Agriculture

Nevertheless, the potential role of rainfed agriculture in contributing to world food production is a subject of debate, and forecasts regarding the relative roles of irrigated and rainfed agriculture vary considerably. Rosegrant *et al.* (2002a) project that more than 50% of additional grain production will come from rainfed areas, particularly in developed countries, while developing countries will increase their imports of grains. The FAO (Food and Agriculture Organization of the United Nations) foresees that the contribution to global food supply from rainfed areas will decline from 65% today to 48% in 2030 (Bruinsma, 2003), offset by productivity improvements and irrigated area expansion. Referring to mixed results of past efforts to enhance productivity in rainfed areas, Seckler and Amarasinghe (2000) are less optimistic concerning the potential of rainfed areas. They foresee that only 5% of the increase in future grain production will come from rainfed agriculture, while the major part will originate from irrigated areas. Further, while numerous studies document the benefits of upgrading rainfed agriculture (Agarwal and Narain, 1999; Wani *et al.*, 2003c), upscaling successes proved challenging. Water-harvesting techniques have long been known, but adoption rates have been low due to low profitability of agriculture, lack of markets, relatively high labour costs and high risks. Yields are highly dependent on economic incentives and crop prices, and a high-yield scenario will only happen if it is profitable for individual farmers (Bruinsma, 2003).

Others counter that compared with irrigated agriculture, investments have been very small, mainly targeted to soil conservation rather than water harvesting (Rockström *et al.*, 2007; Wani *et al.*, Chapter 1, this volume). And particularly in sub-Saharan Africa, irrigation investments have been a mixed success. Inocencio *et al.* (2006) report a success ratio of 50% for new construction projects in sub-Saharan Africa.

Two scenarios

To contrast these optimistic and pessimistic views on the potential of rainfed agriculture and assess risks, the Comprehensive Assessment of Agricultural Water Management[1] developed two scenarios on the development of rainfed agriculture. The optimistic high-yield scenario assumes that prices and incentives are right and physical and institutional arrangements are in place (markets, roads, extension services and credit facilities). Low adoption rates of water-harvesting measures and supplemental irrigation are, on the other hand, assumed for the pessimistic low-yield scenario. Both scenarios are formulated based on exploitable yield gaps, using the Global Agro-Ecological Zones. The FAO and the International Institute for Applied Systems Analysis (IIASA) developed a method for assessing land suitability classes and maximum attainable yields under different input regimes using the Agro-Ecological Zones (AEZ) concept[2]. To reach maximum attainable yields, high input levels and best suitable varieties are needed, depending on the quality of land. This approach provides realistic estimates based on known techniques, without assuming major breakthroughs (Fischer *et al.*, 2002). The difference between maximum attainable and actual yield is referred to as the yield gap. The portion of the gap that can be bridged by differences in crop management is termed the 'exploitable yield gap'. Even among countries with fairly similar agroecological environments, yields differ considerably. Exploitable yield gaps are typically high in low-yield areas, as in sub-Saharan Africa (Molden *et al.*, 2007b). The high-yield scenario assumes that 80% of the gap will be bridged by the year 2050, as a result of successful institutional reform, well-functioning markets and credit systems, mechanization, improved use of fertilizers and high-yielding varieties, and rapid adoption of water-harvesting techniques. Where yields are currently low, productivity improves at a higher rate than observed historically, while in OECD (Organization for Economic Cooperation and Development) countries, where yields are already high and the exploitable gap is small, projected growth rates are relatively low. The pessimistic yield scenario assumes that only 20% of the yield gap will be bridged, owing to a slow rate of adoption of soil fertility and crop improvements, *in-situ* soil and water management, and external water-harvesting measures.

The scenarios are implemented using the WATERSIM model, a quantitative model consisting of two fully integrated modules: a food production and demand module based on a partial equilibrium framework, and a water supply and demand module based on a water balance and water accounting framework (de Fraiture, 2007). Food demand projections are based on a baseline scenario developed for the Comprehensive Assessment and are comparable to other published forecasts (FAO, 2006). In this middle-of-the-road food demand scenario, cereal demand will increase by 62% by 2050, to a large extent because of increased demand for livestock products and hence feed grains. Meat and vegetable demand will roughly double. The scenarios do not take into consideration increased demand for crops for biofuels, which at present constitute a small percentage of total food demand but may increase rapidly in future (Berndes, 2002). The scenarios assume that all additional agricultural demand is met from improved yields on existing rainfed areas and where necessary an expansion of rainfed areas.

Results: Comparing an Optimistic and Pessimistic Scenario[3]

Under the optimistic scenario all additional food demand by 2050 can be met from rainfed agriculture by improved yields combined with a modest increase in agricultural area by 7%. Rainfed cereal yields grow by 72% on a global average but more than double in low-yield areas, particularly in sub-Saharan Africa. Asia, Latin America and sub-Saharan Africa will be self-sufficient in main food crops for the most part. But the Middle East and North Africa must import food because of the lack of rain and suitable lands for rainfed agriculture. The scenario analysis shows that upgraded rainfed agriculture can produce the food required in future, but this will only happen if certain conditions are met. The required productivity increases will not occur without substantial investments in water harvesting, agricultural research, supporting institutions and rural infrastructure. In addition, crop yields will vary with economic incentives and crop prices, as farmers respond to those parameters when choosing key inputs. High yields only materialize if they are profitable for farmers (Bruinsma, 2003). Problems include the lack of domestic market infrastructure, trade barriers to international markets, high marketing costs, poor governance, institutional disincentives to profitable agriculture (taxes, corruption, lack of formal land titles) and high levels of risk discouraging farmers from investing in labour and other inputs. Without investments in supporting physical infrastructure (particularly transport) and more importantly governance and institutions, agricultural development will fail. Resources are available to improve rainfed agriculture, but the institutional structure must encourage farm-level adoption of the recommended production practices.

The environmental and social costs of a failed 'rainfed strategy' can be substantial, as the pessimistic yield scenario shows. If high yields do not materialize and only 20% of the yield gap is bridged, the rainfed area will need to be expanded by 400 million ha to meet food demand by 2050, an increase of 53% compared with 2000. Globally this land is available, particularly in sub-Saharan Africa and Latin America, but such a large expansion might occur at the expense of forests and natural lands, or lead to soil degradation problems if rainfed agriculture is expanded into marginal areas. Countries without potential to expand rainfed areas – due to either lack of suitable land or unreliable rainfall – must increase food imports. In the pessimistic yield scenario, the Middle East and North Africa will import more than two-thirds of their agricultural needs. Owing to lack of suitable land South and East Asia will become major importers of maize and other grains, importing between 30 and 50% of their domestic demand. Latin America, OECD countries and Eastern Europe, having potential to expand land in agriculture, will increase their exports. Globally, food trade will increase from 14% of total agricultural production today to 22% in 2050. There is a risk that poor countries may not be able to afford food imports, and household-level food insecurity and inequity might worsen.

Future food production under the optimistic and pessimistic rainfed scenarios will lead to substantial increases in soil water consumption. Improved water management is a prerequisite for the yield improvements in the high-yield scenario. With higher yields, transpiration by crops must increase to produce enough biomass and economic yield. Part of the increased evapotranspiration might be offset by higher water productivity, by improving the harvest index, by reducing losses from soil evaporation, or by increasing transpiration while reducing evaporation. When yields are low, the scope to improve water productivity is high. But if yields are high, additional water is required to achieve even higher yields (Molden *et al*., 2007b). In the optimistic rainfed yield scenario, total evapotranspiration on cropland increases by 30%, from 7130 to 9280 km^3. While the global average cereal yield improves by 72%, crop water productivity improves by 35%. In the pessimistic yield scenario, global cereal yields improve by 20% and water productivity by 10%, while soil water depletion increases by 60% to 8960 km^3, an additional 4300 km^3 compared with 2000. Increases in soil water depletion of that order of magnitude will have impacts on river flows and groundwater recharge, causing issues regarding downstream water users and those relying on groundwater resources.

Reducing risks

Relying on rainfed agriculture poses substantial risks to farmers because of high temporal and spatial variations. Harvests are always at risk because of frequent short dry spells during the growing season, which reduce the volume of yields (Barron *et al*., 2003). They also have an indirect impact on cultivation, as farmers are less likely to invest in inputs and land management due to the high risk of crop failure. Many water-harvesting techniques are useful to bridge short dry spells but longer dry spells may lead to total crop failure. To get an indication of risks we ran the optimistic and pessimistic scenarios for four different river basins in India over 30 years and counted the number of years in which yields were reduced due to water stress by at least 20% and 40%, respectively. The WATERSIM model uses the linear crop yield reduction function developed by the FAO[4]. To differentiate between different climate zones we used the aridity index (AI), defined as precipitation divided by potential evapotranspiration. Areas with an AI of more than 0.65 are classified as humid. In semi-humid and semi-arid areas the AI falls in the range 0.65–0.4 and 0.2–0.4, respectively. Where the AI is smaller than 0.2, the area is arid. The optimistic scenario, in which enabling conditions for water-harvesting measures are met, assumes that the amount of rainwater falling on the field that can be beneficially used by plants (i.e. effective precipitation as defined by the FAO[5]) is augmented by 30%. Measures to enhance effective precipitation include *in-situ* soil and water management techniques such as conservation agriculture, bunds, terracing, contour cultivation, furrows and land levelling. *Ex-situ* water-harvesting measures for supplemental irrigation consist of surface microdams, subsurface tanks and farm ponds. The pessimistic scenario, in which adoption rates of these measures are low (due to low profitability and lack of market access), assumes an enhancement of effective precipitation of only 10%.

In the humid basin, cereal yields do not suffer from water stress except in a few dry years (Table 7.1). By contrast, in the arid and semi-arid basins, yield reduction of at least 20% due to water stress occurs in 50–67% of the years. By enhancing the amount of rainfall that can be beneficially used by 30%, the number of years that yield reduction occurs in semi-arid areas can be drastically reduced, to one-third of the time. In the arid basin, where rainfall is low compared with potential evapotranspiration, enhancing effective precipitation has a relatively modest effect on risk reduction. The results show that from a biophysical point of view, with appropriate measures, risk of yield reduction due to water stress can be mitigated. This will improve yields by mitigating water stress and by creating a favourable environment for farmers to invest in yield-enhancing inputs.

Conclusion: Upgrading Rainfed Agriculture Offers Good Potential to Meet Future Food Demand

There are compelling reasons to invest in upgrading rainfed agriculture. Many rural poor depend on rainfed agriculture rather than irrigated agriculture. Targeting the poor implies focusing on smallholders in rainfed areas. Investment costs per ha to upgrade rainfed areas tend to be relatively low and, particularly in sub-Saharan Africa, where most rural poor live in rainfed areas, more poor persons are lifted out of poverty by focusing investment to rainfed areas rather than irrigated agriculture. Realizing the potential of existing rainfed areas reduces the need for new large-scale irrigation development. On the other hand, improving rainfed production through water harvesting and supplemental irrigation also requires infrastructure and is likely to affect surface water and groundwater resources downstream.

Current yields in many rainfed settings are low, suggesting that there is good potential to improve harvests and output per unit of rainwater. In an optimistic yield-growth scenario, in which 80% of the gap between actual and obtainable yields is bridged, 85% of projected food demand by 2050 can be met by improving productivity of existing lands. An expansion of rainfed land by 7% is needed to meet all additional food demand.

But relying largely on rainfed agriculture is also risky. Water-harvesting techniques are useful in bridging short dry spells, but longer dry spells can lead to crop failure. Because of this risk, many farmers are reluctant to use fertilizers, pesticides and labour in rainfed settings. Cost of failure is higher, for the individual farmer who loses his/her income and for society. In a pessimistic yield-growth scenario, where technology adoption rates are low, rainfed areas expand up to 60%, leading potentially to encroachment of marginal lands, natural areas and forests. Risks to the individual farmers can be mitigated by appropriate measures in rainwater harvesting, increasing the amount of rainwater that can be beneficially used by crops (i.e. effective precipitation). For example, in the semi-arid basin, risk of yield reduction due to water stress was reduced from 57 to 33% by augmenting effective precipitation by 30%. With the right incentives and measures to mitigate risks to individual farmers, water management in rainfed agriculture holds a large potential to increase food production and reduce poverty while maintaining ecosystem services.

Table 7.1. Percentage of years in which yield reduction due to water stress occurs in cereals excluding rice[a].

Description	Humid (Ganges Basin)		Semi-humid (Cauvery Basin)		Semi-arid (Krishna Basin)		Arid (Indus Basin)	
Yield reduction	> 20%	> 40%	> 20%	> 40%	> 20%	> 40%	> 20%	> 40%
Pessimistic[b]	0%	0%	37%	7%	57%	27%	67%	20%
Optimistic[c]	3%	0%	13%	3%	33%	7%	50%	10%

[a]Source: WATERSIM model simulation. Data: precipitation over 1961–1990 (CRU_TS 2.0); evapotranspiration 1961–1990 Water Gap 1.0; [b]Scenario: 10% enhancement of effective precipitation; [c]Scenario: 30% enhancement of effective precipitation.

Notes

[1] http://www.iwmi.cgiar.org/Assessment/ and synthesis book by Molden (2007).

[2] http://www.iiasa.ac.at/Research/LUC/GAEZ/index.htm?sb=6

[3] Details of the scenarios analysis and results are given in de Fraiture *et al.* (2007).

[4] Yield reduction = ky.ETa/ETp; see Doorenbos and Kassam (1979) with ky = crop factor; ETa = actual evapotranspiration; and ETp = potential evapotranspiration.

[5] http://www.fao.org/docrep/S2022E/s2022e00.htm

References

Abdulai, A. and Hazell, P. (1995) The role of agriculture in sustainable development in Africa. *Journal of Sustainable Agriculture* 7(2/3), 101–119.

Agarwal, A. and Narain, S. (1999) *Making Water Management Everybody's Business: Water Harvesting and Rural Development in India*. Gatekeeper Series 87. International Institute for Environment and Development, London, UK.

Alcamo, J., Döll, P., Kaspar, F. and Siebert, S. (1997) *Global Change and Global Scenarios of Water Use and Availability: an Application of WaterGAP 1.0*. University of Kassel, Centre for Environmental Systems Research, Kassel, Germany.

Anderies, J.M., Ryan, P. and Walker, B.H. (2005) Loss of resilience, crisis and system in south-eastern Australia. *Ecosystems* 9(6), 865–878.

Barron, J., Rockström, J., Gichuki, F. and Hatibu, N. (2003) Dry spell analysis and maize yields for two semi-arid locations in East-Africa. *Agricultural and Forest Meteorology* 177(1–2), 23–37.

Berndes, G. (2002) Bioenergy and water – the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change* 12, 253–271.

Bruinsma, J. (2003) *World Agriculture: Towards 2015/2030. An FAO Perspective*. Food and Agriculture Organization, Rome, Italy; and Earthscan, London, UK.

Bunn, S.E. and Arthington, A.H. (2002) Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management* 30(4), 492–507.

de Fraiture, C. (2007) Integrated water and food analysis at the global and basin level. An application of WATERSIM. In: Craswell, E., Bonell, M., Bossio, D., Demuth, S. and van de Giesen, N. (eds) *Integrated Assessment of Water Resources and Global Change. Water Resource Management*. Springer, Dordrecht, the Netherlands, pp. 185–198.

de Fraiture, C., Wichelns, D., Rockström, J. and Kemp-Benedict, E. (2007) Looking ahead to 2050: scenarios of alternative investment approaches. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 91–145.

DFID (Department for International Development) (2002) *Better Livelihoods for Poor People: the Role of Agriculture*. Issues Paper. Consultation Document Draft A4. Rural Livelihoods Department, London, UK.

Doorenbos, J. and Kassam, A.H. (1979) *Yield Response to Water*. Irrigation and Drainage Paper No. 33. FAO, Rome, Italy.

Falkenmark, M. and Rockström, J. (2004) *Balancing Water for Humans and Nature: the New Approach in Ecohydrology*. Earthscan, London, UK.

FAO (Food and Agriculture Organization of the United Nations) (2006) *World Agriculture: Towards 2030/2050. Interim Report*. FAO, Rome, Italy.

FAOSTAT (2000) UN Food and Agriculture Organization Statistical Database. FAO, Rome, Italy. (Data from 2000.) (http://faostat.fao.org/).

FAOSTAT (2003) UN Food and Agriculture Organization Statistical Database. FAO, Rome, Iitaly. (Data from 2003.) (http://faostat.fao.org/).

FAOSTAT (2005) UN Food and Agriculture Organization Statistical Database. FAO, Rome, Italy. (Data from 2005.) (http://faostat.fao.org/).

Fischer, G., van Velthuizen, H., Shah, M. and Nachtergaele, F.O. (2002) *Global Agro-ecological Assessment for Agriculture in the 21st Century: Methodology and Results*. CD-ROM. International Institute for Applied Systems Analysis, Laxenburg, Austria; and Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

IFAD (International Fund for Agricultural Development) (2001) *Rural Poverty Report 2001: the Challenge of Ending Rural Poverty*. Oxford University Press, Oxford, UK, pp. 229–236.

Inocencio, A., Merrey, D., Tonosaki, M., Maruyama, A., de Jong, I. and Kikuchi, M. (2006) *Costs and Performance of Irrigation Projects: a Comparison of sub-Saharan Africa and Other Developing Regions*. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Irz, X. and Roe, T. (2000) Can the world feed itself? Some insights from growth theory. *Agrekon* 39(3), 513–528.

Johnston, D.G. and Mellor, J.W. (1961) The role of agriculture in economic development. *American Economic Review* 51(4), 566–593.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. (2005) Meta-analysis to assess impact of watershed program and people's participation. *Comprehensive Assessment of Water Management in Agriculture Research Report 8*. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Koning, N. (2002) *Should Africa Protect its Farmers to Revitalise its Economy?* Gatekeeper Series 105. International Institute for Environment and Development (IIED), London, UK.

Lundqvist, J., Barron, J., Berndes, G., Berntell, A., Falkenmark, M., Karlberg, L. and Rockström, J. (2007) Water pressure and increases in food and bioenergy demand: implications of economic growth and options for decoupling. In: *Scenarios on Economic Growth and Resource Demand*. Background report to the Swedish Environmental Advisory Council memorandum 2007:1. SOU, Stockholm, Sweden, pp. 55–151.

MEA (Millennium Ecosystems Assessment) (2005a) *Ecosystem Services and Human Well-being. Wetlands and Water Synthesis*. Water Resources Institute, Washington, DC, USA.

MEA (Millennium Ecosystems Assessment) (2005b) *Ecosystem Services and Human Well-being: Biodiversity Synthesis*. Water Resources Institute, Washington, DC, USA.

Molden, D. (ed.) (2007) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK; and International Water Management Institute (IWMI), Colombo, Sri Lanka.

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., Sadoff, C. and Finlayson, C.M. (2007a) Trends in water and agricultural development. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK; and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 57–89.

Molden, D., Oweis, T., Steduto, P., Kijne, J.W., Hanjra, M.A. and Bindraban, P.S. (2007b) Pathways for increasing agricultural water productivity. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK; and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 219–310.

Revenga, C., Brunner, J., Henniger, N., Kassem, K. and Payner, R. (2000) *Pilot Analysis of Global Ecosystems, Freshwater Systems*. World Resources Institute, Washington, DC, USA.

Richter, B.D., Braun, D.P., Mendelson, M.A. and Master, L.L. (1997) Threats to imperiled freshwater fauna. *Conservation Biology* 11(5), 1081–1093.

Rockström, J. and Falkenmark, M. (2000) Semiarid crop production from a hydrological perspective: gap between potential and actual yields. *Critical Reviews in Plant Science* 19(4), 319–346.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapour flows, food production and terrestrial ecosystem services. *Conservation Ecology* 3(2), 5. (www.consecol.org/vol3/iss2/art5).

Rockström, J., Hatibu, N., Oweis, T.Y. and Wani, S. (2007) Managing water in rainfed agriculture. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK; and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–352.

Rosegrant, M., Cai, X. and Cline, S. (2002a) *World Water and Food to 2025. Dealing with Scarcity*. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Rosegrant, M., Ximing, C., Cline, S. and Nakagawa, N. (2002b) *The Role of Rainfed Agriculture in the Future of Global Food Production*. EPTD Discussion Paper 90. International Food Policy Research Institute (IFPRI), Washington, DC, USA (http://www.ifpri.org/divs/eptd/dp/papers/eptdp90.pdf).

Rosegrant, M.W., Ringler, C., Benson, T., Diao, X., Resnick, D., Thurlow, J., Torero, M. and Orden, D. (2006) *Agriculture and Achieving the Millennium Development Goals*. World Bank, Washington, DC, USA.

Seckler, D. and Amarasinghe, U. (2000) Water Supply and Demand, 1995 to 2025. In: *IWMI, Annual Report 1999–2000*. IWMI, Colombo, Sri Lanka, pp. 9–17.

Seckler, D., Amarasinghe, U., Molden, D., de Silva, R. and Barker, R. (1998) *World Water and Demand and Supply, 1990 to 2025: Scenarios and Issues*. Research Report 19. International Water Management Institute (IWMI), Colombo, Sri Lanka.

SEI (Stockholm Environment Institute) (2005) *Sustainable Pathways to Attain the Millennium Development Goals – Assessing the Role of Water, Energy and Sanitation*. Document prepared for the UN World Summit, September, New York.

Shiklomanov, I. (2000) Appraisal and assessment of world water resources. *Water International* 25(1), 11–32.

Szabolcs, I. (1994) Geostatistical modelling of salinity as a basis for irrigation management and crop selection – a case study in central Tunisia. *Environmental Geology and Water Sciences* 20(2), 85–92.

Tanji, K.K. (1990) Nature and extent of agricultural salinity. In: Tanji, K.K. (ed.) *Agricultural Salinity Assessment and Management*. ASCE Manual Reproduction of Engineering Practices 71. New York, USA.

Thirtle, C., Beyers, L., Lin, L., Mckenzie-Hill, V., Irz, X., Wiggins, S. and Piesse, J. (2002) *The Impacts of Changes in Agricultural Productivity on the Incidence of Poverty in Developing Countries.* DFID Report 7946. Department for International Development, London, UK.

Timmer, C.P. (1988) The agricultural transformation. In: Chenery, H. and Srinivasan, T.N. (eds) *Handbook of Development Economics*, Vol. 1. Elsevier, Amsterdam, the Netherlands, pp. 275–331.

Wani, S.P., Pathak, P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003a) Improved management of Vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19(3), 217–222.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003b) Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK; and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 199–215.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003c) Farmer participatory integrated watershed management: Adarsha watershed, Kothapally, India, An innovative and upscalable approach. Case 7. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council, Consultative Group on International Agricultural Research, Washington, DC, USA, pp. 123–147.

Wani, S.P., Joshi, P.K., Raju, K.V., Sreedevi, T.K., Mike Wilson, Amita Shah., Diwakar, P.G., Palanisami, K., Marimuthu, S., Ramakrishna, Y.S., Meenakshi Sundaram, S.S. and D'Souza, M. (2008) *Community Watershed as Growth Engine for Development of Dryland Areas – Executive Summary*. A Comprehensive Assessment of Watershed Programs in India. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

WCD (World Commission on Dams) (2000) *Dams and Development: a New Framework for Decision-making*. Earthscan, London, UK.

World Bank (1982) *World Development Report 1982*. Oxford University Press, New York, USA.

World Bank (2000) Spurring agricultural and rural development. In: *Can Africa Claim the 21st Century?* World Bank, Washington, DC, USA, pp. 170–207.

World Bank (2005) *Agricultural Growth for the Poor: an Agenda for Development*. World Bank, Washington, DC, USA.

8 Opportunities for Improving Crop Water Productivity through Genetic Enhancement of Dryland Crops

C.L.L. Gowda,[1]* R. Serraj,[5] G. Srinivasan,[2] Y.S. Chauhan,[4]*** B.V.S. Reddy,[1]**** K.N. Rai[1]***** S.N. Nigam,[1] P.M. Gaur,[1] L.J. Reddy,[1] S.L. Dwivedi,[1] H.D. Upadhyaya,[1] P.H. Zaidi,[3] H.K. Rai,[3] P. Maniselvan,[3] R. Follkerstma[6] and M Nalini[1]**

[1] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India;* [2] *University of California, Fresno, USA;* [3] *CIMMYT's Asia Regional Office, Patancheru 502 324, Andhra Pradesh, India;* [4] *Department of Primary Industries and Fisheries, Kingaroy, Queensland, Australia;* [5] *Crop & Environmental Sciences Division, International Rice Research Institute, DAPO Box 7777, Metro Manila, Philippines;* [6] *De Ruiter Seeds Inc., Leeuwenhoekweg 522661, CZ, Bergschenhoek, the Netherlands;*
*emails: *c.gowda@cgiar.org; **r.serraj@cgiar.org; ***yash.chauhan@dpi.qld.gov.au; ****b.reddy@cgiar.org; *****k.rai@cgiar.org*

Introduction

The importance of water as a major limiting factor in agriculture is increasing due to the unpredictable nature of rainfall and increasing demand for water from domestic and industrial users. In arid and semi-arid regions, which experience absolute or economic shortage of water, there is an urgent need to increase crop water productivity (CWP) at the farm level through genetic enhancement and natural resources management. Natural resources and agronomic management options for higher CWP are driven by several factors related to geographic location, governmental policies, crop preferences, marketing issues and involvement of external inputs, often inconvenient or not attractive to rainfed farmers. Because of scale and resource neutrality, the genetic options are amenable to quicker and wider adoption at farm level for increasing CWP.

Pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) (C_4 crops) and the legumes, groundnut (*Arachis hypogaea*), chickpea (*Cicer arietinum*) and pigeonpea (*Cajanus cajan*) (C_3 crops), occupy an important place in the cropping systems of seasonally dry arid and semi-arid tropics (SAT). Maize (*Zea mays*) is an important C_4 crop grown in tropical lowlands, tropical and subtropical mid-altitudes, where drought is a major limiting factor for its production and productivity. The C_4 crops have higher photosynthetic capacity and are more efficient in nitrogen and water use efficiency (WUE). The legumes fix nitrogen through symbiotic association with *Rhizobium* bacteria, and compensate to a large extent for their lesser WUE.

© CAB International 2009. *Rainfed Agriculture: Unlocking the Potential*
(eds S.P. Wani *et al.*)

Global warming due to climate change will affect grain yields, more so in tropical than temperate regions. The global average temperatures by the year 2100 could progressively rise by up to 6 °C under the business-as-usual scenario (http://www.fao.org/docrep/005/y4252e/y4252e15.htm). Reproductive traits are highly sensitive to high temperature, leading to yield reduction. For example, rice (*Oryza sativa*) grain yield declined by 10% for each 1 °C increase in minimum temperature in the dry season in the Philippines (Peng *et al.*, 2004). A projected 10% yield reduction in maize will bring losses equal to US$2 billion in Africa and Latin America (Jones and Thornton, 2003). The wheat (*Tritium aestivum*) yields in China are expected to decline by 20% in 2070 (Hui *et al.*, 2005), while in South Australia by 13.5–32% under the most likely climate change scenario (Luo *et al.*, 2005).

In this chapter, we discuss the target growing environments and crop sensitivity of pearl millet, sorghum, maize, groundnut, chickpea and pigeonpea to drought; phenotypic screens and natural genetic variations for response to drought; empirical and trait-based breeding methods to enhance drought tolerance; and deployment of emerging biotechnological tools (DNA markers and transgene) to enhance crop adaptation and productivity under drought-stress conditions.

Adaptation in Water-limited Environments

Crop productivity versus survival mechanisms

Response of most crops to soil water deficit can be described as a sequence of three successive stages of soil dehydration. Stage I occurs at high soil moisture when water is still freely available from the soil and both stomatal conductance and water vapour loss are maximal. The transpiration rate during this stage is therefore determined by environmental conditions around the leaves. Stage II starts when the rate of water uptake from the soil cannot match the potential transpiration rate. Stomatal conductance declines to keep transpiration rate similar to the uptake of soil water for maintaining the water balance of the plant. Stage III begins when the ability of stomata to adjust to the declining rate of water uptake from the soil has been exhausted, and stomatal conductance is minimal.

Virtually all major processes contributing to crop yield, including leaf photosynthetic rate, leaf expansion and growth, are inhibited late in Stage I or in Stage II of soil drying (Serraj *et al.*, 1999). At the end of Stage II, these growth-supporting processes have reached zero and no further growth occurs in the plants. The focus of Stage III is survival and water conservation, essential for the plant to endure these severe stresses. Plant survival is a critical trait in dryland ecosystems, but for most agricultural situations, Stage III has little relevance to increasing crop yield and water productivity, especially in the case of intermittent drought.

Consequently, the amount of water extracted up to the end of Stage II determines cumulative growth by plants on a particular soil water reservoir. Research on soil water use in crop growth dating >100 years has consistently shown an intimate and stable relationship between the plant growth and transpirational water use after correcting for variations in atmospheric humidity (Sinclair *et al.*, 1984). Therefore, options to enhance crop survival do not usually mean an increase in crop yield under drought conditions. Increased crop yields and water productivity require optimization of the physiological processes involved in critical stages (mainly Stage II) of plant response to dehydration.

Target environments and crop sensitivity to drought

Pearl millet

Post-flowering (also referred to as terminal) drought stress, either alone or in combination with pre-flowering drought, is common in major pearl millet-growing environments in India. Flowering and grain-filling periods are most sensitive to water stress in pearl millet (Mahalakshmi *et al.*, 1987). Yield reduction in this stage is due to decreased panicle number and grain mass. Usually, the number of grains per panicle is less affected if terminal stress occurs after flowering. The reduction in grain mass observed during terminal drought seems to be due to restriction of the assimilate supply rather than due to reduction of the grain storage capacity (Bieler *et al.*, 1993). Under very low water potentials, stomatal closure, and a consequent reduction in photosynthetic activity, has been reported in pearl millet (Henson *et al.*, 1984). However, the supply of assimilates through the mobilization of stored soluble sugars can compensate for the impaired photosynthetic activity (Fussell *et al.*, 1980). The transfer of assimilates from the leaves, with stems serving as a buffer during the grain development, appears to be the main adaptation trait during terminal drought stress in pearl millet (Winkel and Do, 1992). From a study involving normal and extended day length, Mahalakshmi and Bidinger (1985) suggested that photoperiod control of floral initiation can provide an escape mechanism to avoid the coincidence of mid-season water stress with sensitive stages of millet growth.

Sorghum

Terminal drought is the most limiting factor for sorghum production worldwide. In sub-Saharan Africa drought at both seedling establishment and grain-filling stages is very common. In India, sorghum is grown during both rainy and post-rainy seasons. The variable moisture environment during the rainy season can have a severe impact on grain and biomass yield, affecting both pre-flowering and post-flowering stages. Climatic variability and associated genotype × environment interactions do not permit clear definition of the target environments. Opportunities to make progress in breeding for drought tolerance lie both in understanding the environmental control of crop growth and in developing simplified approaches to modelling (Bidinger *et al.*, 1996).

Drought and/or heat stress at the seedling stage often results in poor emergence, plant death and reduced plant stands. Severe pre-flowering drought stress results in drastic reduction in grain yield. Post-flowering drought-stress tolerance is indicated when plants remain green and fill grain normally. The stay-green trait has been associated with post-flowering drought in sorghum. Genotypes with the stay-green trait are also reported to be resistant to lodging and charcoal rot.

Maize

Inadequate water availability at critical stages of crop growth and development is the major limiting factor for maize production and productivity in the tropics. Mean rainfall during the crop season appears to be adequate for maize production, but its distribution during the crop cycle has a high coefficient of variability. Normal interseasonal fluctuations in rainfall have been found to be associated closely with variations in average national maize yields across quite large production regions in the tropics (Edmeades *et al.*, 1995), suggesting that water stress is the pervasive cause of yield instability in maize-based cropping systems in the tropics.

Maize is particularly sensitive to water stress in the period 1 week before to 2 weeks after flowering. Stage-sensitivity in maize to drought stress has been studied extensively. Probability of drought in maize-growing environments in the tropics is highest at the start and end of the rainy season, and therefore the crop is prone to facing water deficit at establishment and flowering/grain-filling stages (Banziger *et al.*, 2000a). Monthly rainfall totals in the tropics have a high coefficient of variability, even though mean rainfall appears adequate for maize production. Although the probability of drought stress is lower at silking, its consequences on yield can be highly severe, since the crop is highly susceptible to drought at this stage (Shaw, 1976). Stress from mid- to late grain-filling also reduces grain yields but relatively less in comparison to silking-stage water deficit.

Drought at flowering commonly results in barrenness in genotypes having a longer anthesis–silking interval (ASI). One of the main causes is reduction in the flux of assimilate to the developing ear below some threshold level necessary to sustain grain formation and growth (Westgate and Bassetti, 1990; Schussler and Westgate, 1995). Drought coinciding with this growth period can cause serious yield instability at the farm level. Understanding the nature of the higher grain potential and enhanced yield stability, especially in stress-prone environments, will provide opportunities to improve the selection of stress-tolerant genotypes.

There is an increase in the ASI and a concomitant increase in the number of barren plants in maize under drought (Zaidi *et al.*, 2003a). A short ASI is considered an indication of the diversion of an increased fraction of the plant's current photosynthesis to the ear, since it is associated with rapid ear growth (Zaidi *et al.*, 2003b). Drought at flowering also affects carbohydrate metabolism of the developing ovule, further reducing sucrose flux to the newly formed seed (Schussler and Westgate, 1995).

Groundnut

The effect of drought on groundnut is manifested in several ways, affecting both quantity and quality of the crops (Nigam *et al.*, 2002). The three patterns of drought observed in groundnut are early-season, mid-season, and end-of-season drought. A 20- to 25-day moisture stress early in the season (once the crop is established) and its subsequent release by irrigation (or rainfall) has been found to induce heavy and uniform flowering, leading to increased productivity. Groundnut shows increased sensitivity to mid-season stress compared with early- and late-season stresses (Pallas *et al.*, 1979) (Fig. 8.1). Yield progressively decreases as duration of the drought increases and as the mid-season approaches. Water deficit during the late flowering and pod-forming periods is detrimental to groundnut yield (Stansell and Pallas, 1985). End-of-season drought affects seed development and its quality (Reddy *et al.*, 1994).

Moisture-stress timing and severity during flowering decreases the number of flowers and delays the time to flower. However, since only 15–20% of flowers form pods, reduction in flowering due to moisture stress does not directly influence pod yield (Nageswara Rao *et al.*, 1988). Also, groundnut can compensate for reduced flower numbers arising from water deficits by producing a flush of flowers once the stress is relieved (Pallas *et al.*, 1979; Nageswara Rao *et al.*, 1988). Soil water deficits during pegging and pod set decrease yield primarily by reducing pod number rather than seed mass per pod (Boote *et al.*, 1976), which is true only if there is sufficient water available for the production of assimilates at the later stage (Harris *et al.*, 1988). Owing to the subterranean fruiting habit of groundnut, a reduction in soil water content can have a dual effect on peg and pod development. While the root-zone water content can directly affect plant water status and photosynthesis (and hence assimilate supply to developing pegs and pods), the water content in the pegging and podding zones can affect reproductive growth independent of the root-zone moisture content. The pod-zone water content influences peg pene-

Fig. 8.1. Contrast among groundnut genotypes for early water use and wilting.

tration and conversion into pods, and calcium and water uptake by pods (Boote *et al.*, 1982).

Variability for maturity duration in groundnut germplasm offers the possibility of selecting genotypes with desired phenology to match the environment. In the regions where the growing season is longer, cultivars belonging to the Virginia type are generally cultivated; in areas where the season is shorter, Spanish and Valencia types are cultivated. With the perceivable changes in global temperature and rainfall patterns, it may become necessary to match genotypes more carefully to the length of growing season. For example, groundnut production in Nigeria has reduced drastically over the past few years because of severe droughts. The isohyets movement towards the south has resulted in the shortening of the period of useful rains in northern Nigeria. This has necessitated the shift from growing long-duration genotypes to short-duration genotypes (Gibbons, 1978). Agroclimatological analysis of major rainfed (75–90 days) groundnut environments in the SAT indicates that growing areas in the SAT are characterized by short growing seasons, i.e. 75–110 days (Virmani and Singh, 1986). This explains the better performance of short-duration genotypes in West African regions.

Chickpea

Characterizing drought in post-rainy season crops such as chickpea is relatively simple, compared with the intermittent drought experienced by the rainy-season crops. As the crop is grown almost entirely on stored soil moisture, it is exposed mostly to progressively increasing (terminal) water deficit. Factors governing crop growth and water use in the post-rainy season, i.e. radiation, temperature, vapour pressure and potential evaporation, are relatively stable and predictable. Hence simulation modelling of both crop growth and the effects of various crop traits is eminently feasible.

Pigeonpea

Throughout the SAT regions of South Asia and Africa, where much of the pigeonpea is grown, rainfall is erratic in its amount and distribution. However, based on the long-term rainfall pattern, it is possible to broadly characterize patterns of drought in a given environment by calculating probabilities of dry periods followed by wet periods or vice versa (Virmani *et al.*, 1982). This assessment is helpful in developing genotypes for target environments or in identifying environments with similar drought patterns. Traditionally, medium- to long-duration landraces have been cultivated, with a crop duration of 150–300 days. Pigeonpea can be exposed to intermittent drought stress during dry periods of the rainy season and to terminal drought stress in the post-rainy season. Since the late 1980s, short-duration genotypes have been developed, with extra-short-duration genotypes able to reach maturity within 90 days (Nam *et al.*, 1993). However, the short-duration genotypes are usually sensitive to intermittent drought. A pigeonpea simulation model (Robertson *et al.*, 2001) could also facilitate characterization of drought patterns for environments where long-term weather data is available.

Phenotypic Screens and Natural Genetic Variations for Drought Tolerance

Pearl millet

The line-source sprinkler irrigation method, earlier developed by Hanks *et al.* (1976), is used to screen pearl millet for drought tolerance. It provides gradients of drought stress, which allows the evaluation of large numbers of genotypes at varying intensity of drought in a given environment. However, where response to applied water is linear, simpler stress/no stress techniques provide a more efficient means of conducting preliminary evaluations (Mahalakshmi *et al.*, 1990).

When yield performance under stress is not related to time to 50% flowering, the drought susceptibility index (DSI) is calculated based on yield under rainfed conditions and potential yield under irrigated conditions (Fisher and Maurer, 1978). The lower the DSI, the greater is the drought tolerance. Bidinger *et al.* (1987a,b) modified the DSI method to include cases in which yield under stress was related to drought escape and yield potential; it was thus used for screening pearl millet and identifying tolerant genetic material.

Grain yield in pearl millet can be improved under water-limited environments if specific traits and responses associated with drought tolerance can be identified and incorporated into elite high-yielding genotypes of appropriate crop duration (Bidinger *et al.*, 2000; Yadav *et al.*, 2002). The drought-tolerant lines in pearl millet include 863B, ICMP 83720, ICMV 94472 and PTRLT 2/89–33.

Sorghum

At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, sorghum is evaluated for post-flowering drought tolerance during the post-rainy season. The drought is imposed at flowering/grain development stage by withholding water and lines scored for stay-green trait using curve-fitting of green leaf area retention and/or leaf chlorophyll content (using Minolta Chlorophyll Meter SPAD 502) at regular time intervals. Promising accessions from the field evaluations are further tested for drought response and root traits using a lysimetric system where plants are grown in large and long PVC cylinders, mimicking roughly the soil volume that sorghum plants would have at the usual field planting densities. The plants are grown under well-watered conditions until booting, after which a water-stress treatment is imposed.

Drought-tolerant sources in sorghum include Ajabsido, B35, BTx623, BTx642, BTx3197, El Mota, E36Xr16 8/1, Gadambalia, IS12568, IS22380, IS12543C, IS2403C, IS3462C, CSM-63, IS11549C, IS12553C, IS12555C, IS12558C, IS17459C, IS3071C, IS6705C, IS8263C, ICSV 272, Koro Kollo, KS19, P898012, P954035, QL10, QL27, QL36, QL41, SC414–12E, Segaolane, TAM422, Tx430, Tx432, Tx2536, Tx2737, Tx2908, Tx7000 and Tx7078 (www.icrisat.org). Drought tolerance of M 35–1, a highly popular post-rainy-season-adapted landrace in India, has been demonstrated (Seetharama *et al.*, 1982).

Maize

Various options have been used for screening the germplasm for identification of relative tolerance to water-limited conditions (Bruce *et al.*, 2002). Growth chamber or greenhouse screening may provide highly precise management of intensity, uniformity and timing of stress treatment. However, the findings may have least repeatability in target population environments, which closely represent farmers' fields. These evaluations generally require multiple seasons and a large number of sample environments for judicious judgement on the performance of a cultivar in target environment. Statistical procedures such as genetic correlation among environments, genotype × environment interaction and stability analysis can help improve the process of establishing the reliability of prediction on the performance of genotypes in target population environments (Cooper and DeLacy, 1994).

Managed-stress environments under rain-free season may play an essential role in assuring reproducible stress conditions targeted at specific growth stages. At CIMMYT (International Maize and Wheat Improvement Center), genotypes are screened under three moisture regimes: (i) well watered, where moisture is maintained in the plots as per normal recommendation; (ii) intermediate water stress, where plants are exposed to drought stress during late flowering and throughout grain filling by withdrawing irrigation 1 week before flowering until maturity; and (iii) severe stress, where plants are exposed to drought stress during flowering and the early grain-filling stage by withdrawing irrigation 3 weeks before flowering. Each of the managed moisture conditions is able to expose genetic variation for specific traits. The well-watered condition allows expression of yield potential; the intermediate water-stress regime exposes genetic variation for lower leaf senescence and grain yield; and the severe stress regime exposes the variability for ASI and ears per plant. Selection for drought tolerance is based on grain yield, ASI, ears per plant, stay-green and tassel size, which have shown tremendous gains across the moisture regimes (Edmeades *et al.*, 2000).

The sources of drought tolerance in maize include 95TZEE-W, 95TZEE-Y, Ac7643, Ac7643S_5, Chang 3, CML 269/CML343, CML 449/CML 343, D 978, Danhuang 02, HI 209, HI 295, HI 536, HI1040, K 10, K 22, TSC 8, TZE-COMP 3 DT, X178, Xi 502, Ye 8001, Yedan-13 and Zheng 22 (www.cimmyt.org) (Fig. 8.2).

Fig. 8.2. Available genotypic variability for flowering-stage drought stress in tropical maize.

Groundnut

ICRISAT adopted a holistic approach in screening and selecting groundnut genotypes with superior performance under mid-season and end-of-season drought conditions (Nageswara Rao and Nigam, 2003). An empirical approach was first followed for selection among segregating populations and evaluation of advanced breeding lines for their sensitivity to mid-season and end-of-season droughts, based on pod and seed yields. While the empirical approach was partly successful, it was concluded that a more efficient breeding approach is required for the selection of traits associated with drought tolerance. There has been significant improvement in physiological understanding of the genotypic response to drought in groundnut, suggesting scope for selecting genotypes with traits contributing to superior performance under water-limited conditions. For instance, substantial genetic variation has been observed in partitioning of dry matter to pods (Nageswara Rao *et al.*, 1993). Significant genotypic variation in the total amount of water transpired (T) and transpiration efficiency (TE) has been shown (Wright *et al.*, 1994). Further studies have confirmed large cultivar differences in TE in groundnuts (Hubick *et al.*, 1988; Wright *et al.*, 1994). These studies enabled analysis of the yield variation under drought conditions using a physiological framework proposed by Passioura (1977), where HI = Harvest Index:

$$\text{Pod yield} = T \times TE \times HI$$

Research has also shown that TE and carbon isotope discrimination in leaf (CIDL) are well correlated (Wright *et al.*, 1988), suggesting the possibility of using CIDL as a rapid, non-destructive tool for selection of TE in groundnut. However, further research has shown that specific leaf area (SLA), expressed in cm^2/g, is well correlated with CIDL and TE (Wright *et al.*, 1994).

Several sources of tolerance to mid-season and/or end-of-season drought have been reported in groundnut that showed variation for physiological traits such as SLA, WUE, T, TE, and HI under drought-stress conditions (Dwivedi *et al.*, 2007a). Rucker *et al.* (1995) identified a drought-tolerant, high-yielding line, PI 315628, from pot/field experiments, with the largest root system and low in-canopy temperature.

Chickpea

Both line-source and DSI methods have been found to be very effective in identifying sources of tolerance to terminal drought in chickpea. Sources of drought tolerance identified by the first method (Saxena, 1987) were further validated by the second method (Johansen *et al.*, 1994). The drought-tolerant chickpea accessions include Annigeri (high yield and short duration), ICC 4958 (large root, large seed, rapid partitioning), ICC 10448 (high yield, smaller pinnule, large sink), ICC 5680 (small leaf, fewer pinnules) and JG 62 (twin-podded, rapid partitioning) (Saxena *et al.*, 1993; Saxena, 2003). Kashiwagi *et al.* (2006) perfected a PVC-cylinder-based technique for screening chickpea root traits associated with drought tolerance. Root length density (RLD) at 35 days after sowing showed significant positive correlation with seed yield. Similarly, RLD at different soil depth (15–30 or 30–60 cm) had positive effects on seed yield, more pronounced under severe drought. RLD of plants grown in cylinders with 70% field capacity correlates well with RLD in the field trials. Using this technique, Kashiwagi *et al.* (2005) detected substantial variation in root-length density (RLD) in chickpea landraces collected from the Mediterranean and West Asian regions that showed better drought tolerance than of the known drought-tolerant genotype, ICC 4958. Promising drought-tolerant breeding lines/cultivars include ICCVs 94916–4, 94916–8, 94920–3, 94924–2, 94924–3, and 98901 to 98907, with yields similar to the high-yielding parent (Saxena, 2003).

Pigeonpea

The rainout shelter facility at ICRISAT has significantly improved the precision of drought screening. Chauhan *et al.* (1998) detected substantial genetic differences when they screened 32 pigeonpea lines for drought tolerance at flowering using DSI. ICPL 88039 showed greater drought tolerance than other genotypes. Pigeonpea hybrids ICPH 8 and ICPH 9 were the most drought tolerant and their reaction was further confirmed in multi-location trials.

The drought screening under the rainout shelter, though reliable, has limitations of space and that pigeonpea cannot be grown year after year at the same place. To overcome the latter problem, rainout shelters that can be moved to different places have been designed (Chauhan *et al.*, 1997).

Breeding programmes on pigeonpea in recent years have focused on developing genotypes of 90–150 days maturity (Gupta *et al.*, 1989). This has made it possible to match phenology with periods of soil moisture availability, a proven way of combating terminal drought (Chauhan *et al.*, 1998). Nevertheless, there is considerable yield gap, which is largely due to the adverse effect of intermittent droughts in different environments (Nam *et al.*, 1993). The short-duration pigeonpea and extra-short-duration pigeonpea cultivars are generally shallow rooted (Chauhan *et al.*, 1993), and what they gain by being able to escape terminal drought stress is lost by their inability to extract water from the deeper soil layer. Indeed it is observed that these genotypes extract water from shallower (<75 cm) layers, compared with an unstressed control (Nam *et al.*, 2001). In addition, large gaps within the rainy-season rainfall are not unusual in the semi-arid regions, when extra-short-duration and short-duration cultivars may be forced to grow with limited ability to extract water due to their shallow root system. Therefore, more work is needed for screening and selecting pigeonpea cultivars for intermittent drought tolerance.

Genetic Enhancement for Improved Water Productivity

Drought escape

Pearl millet

Drought escape is a major mechanism in pearl millet, determining relative cultivar performance in individual stress environments (Bidinger *et al.*, 1987a), often a major cause of genotype × environment interaction in multi-environment trials (van Oosterom *et al.*, 1996). For example, if rains end early, a 1-week difference in time to flowering between two cultivars is equivalent to about 30% of the grain-filling period, which enables an early flowering cultivar to escape stress (Mahalakshmi *et al.*, 1988).

The effects of timing of the occurrence of individual periods of stress, before and after flowering provide quantification of the effects of drought escape. For example, an early genotype which flowered 20 days before the onset of a terminal drought stress had about one-quarter of the yield reduction (−12% versus −51%) of a genotype that flowered only 10 days before the onset of the same stress (Mahalakshmi *et al.*, 1987). However, the scope for using this mechanism in crop improvement under drought conditions still depends upon the predictability of the occurrence of stress.

Sorghum

Breeding for earliness has been successful for increasing the yield of rainy-season sorghums in India (Seetharama *et al.*, 1982). Earliness is more advantageous during the post-rainy season, although crop maturing earlier than 3 months may not achieve high yields (Seetharama *et al.*, 1982). In West Africa, phenotypic plasticity derived from photoperiod sensitivity is an important adaptive trait, useful for matching the crop growth and development with the water-availability period.

Groundnut

In most of the groundnut-growing regions in the SAT, the rainfall distribution is erratic and the season length is less than 100 days (Virmani and Singh, 1986). Considerable progress has been made at ICRISAT in shortening the crop duration of groundnut without decreasing the realized yield substantially (Vasudeva Rao *et al*., 1992). The short-duration varieties developed at ICRISAT have shown superior pod yield over local control varieties in several countries. The early-maturing genotypes usually have shallow root systems, which could make them more susceptible to intermittent drought and also result in reduction of the yield potential. However, genotypic differences in rooting depth have been observed in groundnut (Wright *et al*., 1991; Nageswara Rao *et al*., 1993), suggesting the scope for combining early maturity with efficient root system.

Chickpea

Short-duration varieties that mature before the onset of terminal drought have proved successful in increasing yield under drought-prone conditions in chickpea (Kumar *et al*., 1996). However, since seed yield is generally correlated with the length of crop duration under favourable crop-growing conditions, reduction of crop duration below the optimum would have a yield penalty (Saxena, 1987). Depending upon the water availability, optimum crop duration for maximum yield would vary. Hence, varieties need to be matched with the length of growing period (Fig. 8.3). Significant progress has been made in developing improved short-duration chickpea varieties that mature in 80–90 days (Kumar *et al*., 1996) and extra-short-duration varieties (<80 days), which provide options to grow chickpea in many prevailing systems and evolving new production systems, such as rice fallows (Kumar and van Rheenen, 2000).

Pigeonpea

Studies indicate that terminal drought usually reduces the grain yield of landraces growing in their typical environment (Chauhan *et al*., 1992). This is more apparent in the shorter-duration environments closer to the equator, where evapotranspiration is high during the post-rainy season. Thus, in terms of maximizing grain yield, the duration of these landraces seems too long for the period of soil moisture availability. However, there is a large spectrum

Fig. 8.3. An extra-short-duration chickpea variety that escapes terminal drought.

of genotype duration available (Gupta *et al.*, 1989), and matching genotype duration with likely period of soil water availability ensures against terminal drought stress. Further, opting for a shorter-duration cultivar in a region does not necessarily mean a sacrifice in yield potential, as even extra-short-duration pigeonpea varieties can produce yields above 2.5 t/ha (Nam *et al.*, 1993).

Candidate traits for drought tolerance

Pearl millet

The panicle HI, i.e. the ratio of grain to total panicle weight, has been evaluated as a selection criterion for terminal stress tolerance in pearl millet breeding (Bidinger *et al.*, 2000). It is also currently used as one of the traits for which quantitative trait loci (QTLs) are being identified, from a mapping population made from parents that differ in the ability to maintain panicle HI under stress. Panicle HI, however, is readily and inexpensively measured in field experiments and can be used as a direct selection criterion. The main potential benefit to identifying QTLs for panicle HI would be to allow marker-assisted backcross transfer of improved tolerance of terminal stress to elite lines and varieties, without the requirement for extensive field screening (Fig. 8.4).

Sorghum

Delayed senescence or stay-green is considered as a useful trait for plant adaptation to post-flowering drought stress, particularly in environments in which the crop depends largely on stored soil moisture for grain-filling (Fig. 8.5). Morphological traits associated with drought endurance and escape in sorghum include good seedling emergence and vigour, earliness, stay-green, tillering, pollination gap, better seed set and grain-filling, good panicle exsertion and reduced stalk lodging. Glossy trait in sorghum, characterized by light yellow-green leaves with a shiny surface, has been reported to confer a broad-spectrum tolerance to both biotic and abiotic stresses, including drought, high temperature, salinity, diseases and insects (Maiti, 1996). The glossy leaf surface is believed to be due to epicuticular wax. The majority of the 495 accessions with glossy trait identified at ICRISAT are from the Indian peninsula and belong to the taxonomic race *durra*. Many of the genotypes tolerant to drought at the seedling stage are glossy and recover faster once the stress is relieved (Maiti *et al.*, 1984).

Fig. 8.4. Good seed set in the long-panicle pearl millet varieties adds to drought tolerance.

Maize

Grain yield is commonly used as a selection criterion in crop improvement. However, inheritance of yield is complex and its heritability often declines under stress conditions (Bolaños and Edmeades, 1996). Selection on the basis of grain yield per se for improved performance under abiotic stresses has often been misleading and inefficient. Therefore, stress breeding programmes commonly use secondary traits, where heritability of some of these traits, such as ASI and ears per plant, remains relatively high, while the genetic and phenotypic correlations between grain yield and those traits increase sharply under drought and low nitrogen stresses (Bolaños and

Fig. 8.5. The stay-green trait provides enhanced drought tolerance in sorghum.

Edmeades, 1996; Banziger *et al.*, 1997). Edmeades *et al.* (1998) suggested that an ideal secondary trait should be: genetically associated with grain yield, highly heritable, genetically variable, cheap and fast to measure, stable within the measurement period, not associated with a yield penalty under unstressed conditions, easily observed at or before flowering in order to eliminate undesirable parents from being used in crossing, and a reliable estimator of yield potential before final harvest.

Key secondary traits for selecting drought tolerance include reduced barrenness on ears, ASI, stay-green, and to a lesser extent, leaf rolling (Banziger *et al.*, 2000c). Other traits such as root growth are only useful when they have been field-tested and have met the criteria prescribed for an ideal secondary trait. Roots have a very important role in water acquisition and a significant component of tolerance to water-deficit stress (McCully, 1999). When studying the relationship between early root development and grain yield under drought using recombinant inbred lines (RILs) differing in seedling root traits, the RILs with poorer early root development yielded better than those with more vigorous early root development (Bruce *et al.*, 2002). Using stress-adaptive secondary traits along with grain yield in maize has improved the selection gain in yield under low nitrogen stress by 20% in comparison to selection for yield per se (Banziger *et al.*, 1997).

Groundnut

Good scope exists for genetic improvement of the efficiency of crop water use in groundnut (Wright and Nageswara Rao, 1994). Significant genotypic variations in T and TE have been reported in groundnut (Wright *et al.*, 1988) (Fig. 8.6). Groundnut lines ICGS 76, ICGS 44, Tifton 8 and Kadiri 3 were identified with high TE values (Wright *et al.*, 1994). The extent of the root depth and RLD becomes important for soil water extraction during prolonged water deficit. Deep rooting and faster extraction may be very appropriate in tropical environments, where groundnut is grown solely on stored moisture in the dry season on high water-holding capacity soils (Prabowo *et al.*, 1990). Genotypic variability for root characteristics (root volume, root dry weight, root length and number) has been reported in groundnut (Ketring, 1984). However, only minor differences in water extraction patterns and total water use were observed among cultivars (Wright and Nageswara Rao, 1994).

Fig. 8.6. Characterization of the variation in transpiration across growing time of the reference collection of groundnut germplasm using a mini-lysimetric system.

Chickpea

Two important drought-avoidance traits have been characterized and widely used for the genetic enhancement of chickpea at ICRISAT: the large root system (which appears to be useful in greater extraction of available soil moisture) and smaller leaf area (which has been shown to reduce the transpirational water loss) (Fig. 8.7). The chickpea line ICC 4958 has multiple traits of large root size, a rapid rate of root development and extraction of water, and a rapid rate of seed development related to its large seed size. Lines ICC 5680 and ICC 10480 have smaller leaf area, owing to either narrow pinnules (ICC 10480) or fewer pinnules (ICC 5680). Recombinants with traits of ICC 4958 and ICC 5680 showed higher midday leaf relative water content compared with the parents in field trials conducted at ICRISAT (Saxena, 2003).

End-of-season drought is often associated with increasing temperature (Calcagno and Gallo, 1993). Early pod set is considered a prime strategy for avoiding drought stress in environments prone to end-of-season moisture stress (Sedgley *et al.*, 1990). The development of early-maturing varieties may help drought escape and result in stabilizing productivity and assist in extending the chickpea crop to more drought-prone areas.

Pigeonpea

Several mechanisms seem to contribute to adaptation of pigeonpea to drought, which in some cases ensure only its survival but in other cases also have an effect on grain yield. These have been categorized under three strategies: (i) drought escape (e.g. phenological adjustment); (ii) drought avoidance (e.g. deep root systems, stomatal closure, leaf shedding and rolling, paraheliotropic movement, low epidermal conductance); and (iii) drought tolerance (osmotic adjustment, radiation use efficiency, photosynthesis, partitioning of assimilates). Important putative drought-tolerance traits for pigeonpea include early vigour, leaf area maintenance, high root and shoot growth rate, and development plasticity (Johansen, 2003). Early growth vigour is an important factor in drought

Fig. 8.7. Evaluation of chickpea germplasm for transpiration variability by use of a mini-lysimetric system.

resistance as it permits establishment of an effective root system that can extract water during later drought periods. There are considerable differences in early growth vigour of pigeonpea (Johansen, 2003). Early-maturing genotypes generally show more vigour than later-maturing ones, with hybrids showing most vigour, but there are exploitable differences in this trait within maturity groups.

While reduction in leaf area under drought stress would reduce transpirational losses and thus enhance survival ability, leaf area maintenance seems to be an important consideration for pigeonpea under drought (Subbarao *et al.*, 1995). Leaf area maintenance under intermittent drought stress would involve an integration of several lower-level traits, such as a root system effective in water extraction, dehydration tolerance and leaf movements. Leaf area maintenance can be used as morphological marker in a breeding programme. Pigeonpea shows large genotypic differences for this trait (Lopez *et al.*, 1997). The short-duration genotype ICPL 87 performs better than its sister genotype, ICPL 151, which correlates with the greater leaf area retention of ICPL 87 under drought than ICPL 151.

Empirical and Trait-based Approaches to Enhance Drought Tolerance

Plant breeding provides a means of closing the gap between actual and potential yield in stressed environments (marginal and dry areas) through genetic manipulations (Acevedo and Ferreres, 1993). Crops, or cultivars within each crop, are replaced with others having a higher fitness in an environment gradient arising from uncontrolled physical limiting factors. Hence, farmers and breeders attempt to identify crop tolerance in these gradients arising from the specific abiotic stresses. However, the choice of the crop or cultivars within a crop in terms of ‘economic phenotype performance’ are driven by several intricate factors such as genotype, environment, crop management, policies (affecting both people and market), institutional arrangements and social demographics, which make the plant breeders’ job much more complicated (Ortiz *et al.*, 2002).

Pearl millet

Grain yield potential has been considered as a significant factor in determining the yield under moisture stress conditions as well (Bidinger *et al*., 1982; Fussell *et al*., 1991). Improvement in yield potential is expected to result in some improvement under moisture stress, especially under terminal stress and less severe stress conditions. However, this could not be validated under natural drought conditions during the main rainy season (Yadav and Weltzien, 1999). Breeding for wide adaptation has also resulted in selecting genotypes with drought tolerance, such as ICTP 8203 (in India), IKMP 3 and IKMP 5 (in Burkina Faso).

Considerable research has been conducted on the traits themselves, but there are few cases where an individual trait or mechanism has been shown to be sufficiently associated with yield to recommend it as a selection criterion (Mahalakshmi *et al*., 1997). In pearl millet, ability to set and fill grains was found to be related to drought tolerance (Bidinger *et al*., 1987a). Of all the responses related to drought tolerance in pearl millet, panicle HI (ratio of grain mass to the total panicle mass), which integrates both setting and filling of grains, was the best predictor. Therefore, panicle HI can be used as an inexpensive selection criterion in breeding for drought conditions in pearl millet. Panicle HI is a particularly effective variable for post-flowering stress, because the mass of the structural parts of the panicle (which complete their growth prior to flowering) is largely unaffected by stress, whereas the grain mass is significantly affected by both floret abortion and reduced grain-filling (Bidinger and Mukuru, 1995). However, the analysis of predicted response to selection for panicle HI did not indicate that panicle HI would be an effective indirect selection criterion for improved yield under stress in the test-crossed mapping population lines. This is in contrast to the results achieved in the actual selection experiments. This suggests that the requisite (genetic) preconditions for panicle HI to be an effective indirect selection criterion for improved terminal stress tolerance need to be clearly defined.

Sorghum

Breeding for drought tolerance could be linked either to drought-resistance mechanisms and/or to yield. At ICRISAT, a combination of these two approaches with pedigree selection is followed. The drought-tolerant lines selected under mild stress showed high yield potential in stress-free environments; thus it is possible to select for drought tolerance without a concomitant yield decrease in non-stress environment (Rosielle and Hamblin, 1981).

Selections for yield and wide adaptation, determined on the basis of multi-location testing, may or may not be useful in selecting for drought tolerance as the nature, severity and duration of drought stress vary with soil type and weather variables. There is, therefore, a need for a wide range of cultivars and fine-tuning at local levels. Higher green leaf area, delayed onset of leaf senescence, and reduced rate of leaf senescence have been suggested to improve yield under terminal drought situations (Hammer and Muchow, 1994). An approach to breeding for drought tolerance and yield potential at ICRISAT includes: (i) selecting breeding materials for specific traits such as emergence under soil crust; (ii) seedling drought recovery, and grain yield under drought-prone and high-potential areas for early-stage drought; (iii) drought recovery for grain yield under drought-prone and high-potential areas alternatively for mid-season drought; and (iv) stay-green, non-lodging and grain yield under drought-prone and high-potential areas alternatively for terminal drought (Reddy, 1986).

Sorghum hybrids are known to have reduced growth duration, due to higher growth rates, and increased HI (Blum *et al*., 1977), and early-maturing genotypes have shown relative yield advantage under late-season moisture stress (Saeed and Francis, 1983; Saeed *et al*., 1984). Selection for improved productivity under water-stress conditions resulted in a genetic shift towards early flowering but with some yield penalty. Nevertheless, the increased yield potential coupled with greater vigour and earliness of hybrids has been very well exploited to breed for drought tolerance through escape mechanism. The rainy-season hybrids rapidly became the primary components of various production systems in India because of their higher productivity, wider adaptability, short duration and stature (Rana *et al*., 1997). Under terminal water stress during the post-rainy season, early-maturing sorghum genotypes produce equal grain but less dry matter than late-maturing cultivars. Some popular sorghum hybrids with higher water productivity include CSH 8, CSH 18, CSH 16 and JKSH 22. The superior performance of sorghum hybrids over varieties in semi-arid dry areas has been demonstrated in several countries (Kebede and Menkir, 1987; House *et al.*, 1997). Hybrids perform better than varieties under moisture conditions, and also recover faster when moisture stress is released (Osmanzai, 1994).

The stay-green trait expresses best in environments in which the crop is dependent on stored soil moisture but where this is sufficient to meet only a part of the transpiration demand. Sufficient expression of the trait for selection is thus dependent upon the occurrence of a prolonged period of drought stress of sufficient severity during the grain-filling period to accelerate normal leaf senescence but not of sufficient magnitude to cause premature death of the plants (Mahalakshmi and Bidinger, 2002). The stay-green trait from IS 12555 (SC 35) has been successfully used in Australia to develop post-flowering drought tolerance and lodging resistance in parental lines and commercial hybrids (Henzell *et al.*, 1992). Conventional breeding for stay-green has been primarily based on B 35 and KS 19 (Mahalakshmi and Bidinger, 2002). The partially converted (B 35) and fully converted (SC 35C-14E) versions of IS 12555 (Rosenow *et al.*, 1983) have provided the best sources of the trait used in the Australian programme (Henzell *et al.*, 1997). Sorghum hybrids containing the stay-green trait yield significantly more under water-limited conditions compared with hybrids not possessing this trait (Rosenow *et al.*, 1983; Borrell and Douglas, 1996). This advantage is reported to be due to maintenance of photosynthetic capacity and reduced mobilization of stem reserves to grain during the late grain-filling period, combined with lodging resistance (Borrell and Douglas, 1996). In this study, stay-green was not associated with lower HI, as was reported in an earlier study (Rosenow *et al.*, 1983).

Maize

Plant breeders traditionally evaluate their advanced materials in a range of environments. The approach relies on multiple tests of progenies in the environments representing a random selection of the variation in drought stress in the target environment and selection largely on the basis of grain yield (Rosielle and Hamblin, 1981). More recently, Zaidi *et al.* (2004) have demonstrated that with conventional selection under optimal conditions it is likely that some of the best materials with tolerance to drought and/or low-nitrogen stress might have been rejected, while other less desirable materials for marginal and less favourable environments are selected on the basis of their superior performance under optimal input and favourable environments. Plant response to limited water conditions in terms of drought-adaptive traits is only expressed when they are exposed to such conditions, and genetic variability can be identified. Castleberry *et al.* (1984) examined Corn Belt hybrids developed under optimal input conditions from a period of more than 50 years and found very low selection gains under low soil fertility. Similarly, Martinez-Barajas *et al.* (1992) reported that progress from selection for high yield under well-watered conditions was greatly reduced under water-deficit conditions. These results suggest that positive spillover effects from selection under optimal conditions to stress conditions may be limited. Duvick (1995) proposed that the major goal of the tropical maize improvement programme should be to improve and stabilize yield, and broaden adaptation through increased tolerance to various abiotic stresses. For areas where the average maize yield is less than 2.0–2.5 t/ha, selecting genotypes for high yield in these target environments is preferred (Fig. 8.8).

While comparing the suitability of managed-stress versus multi-location testing for improving drought tolerance in maize, Byrne *et al.* (1995) concluded that evaluating the genotypes under managed drought stress, rather than that which occurs randomly during multi-location testing, is relatively more effective and efficient in selecting maize germplasm for water-deficit tolerance. Elapsed time per selection cycle is often less when testing under a few managed environments than under multi-location testing at several sites. Use of modern experimental designs, such as alpha lattices or row and column designs, can further increase selection efficiency (Yau, 1997). Relating the environmental classification, crop modelling and the identification of the target population environments the crop encounters over time suggests

Fig. 8.8. A high-yielding CIMMYT maize hybrid at ICRISAT campus.

that considerable gains can be expected in this area (Chapman *et al.*, 2000).

Recurrent selection for drought tolerance

CIMMYT has made a concerted attempt to select and improve mid-season drought tolerance in tropical maize and identified 50–80 best-performing families that produced high grain yield across the water-stress regimes, small ASI and delayed foliar senescence under severe and intermediate stresses, and adequate yield and small tassels under well-watered conditions (Byrne *et al.*, 1995).

Edmeades *et al.* (1994) demonstrated that gain in yield across two populations (La Posta Sequia and Pool 26 Sequia) averaged 259 kg/ha (12.4% per cycle) under drought, and 115 kg/ha (1.5% per cycle) under well-watered conditions. Yield improvements under drought were paralleled by increases in ears per plant (0.075 per cycle) and in HI, while ASI declined (1.3 days per cycle). Principal component analysis of yields in the ten different environments showed that well-watered and drought environments were generally orthogonal, which indicates that selection only in well-watered environments is unlikely to give improvements in yield under drought. They concluded that selection for drought tolerance has improved broad adaptation, as well as specific adaptation to dry environments. Further studies under two water regimes (well watered and severe drought stress) revealed that yield gains in La Posta Sequia and DTP (drought-tolerant population) averaged 218 and 239 kg/ha/cycle under drought and 55 and 41 kg/ha/cycle under well-watered conditions, respectively. Yield improvements under drought were paralleled by increases in ears per plant and HI, while ASI declined (Srinivasan *et al.*, 2003). Bruce *et al.* (2002) also reported average improvement in grain yield of 126 kg/ha/cycle, following recurrent selection under drought conditions.

Gains from multi-environments evaluation

Zaidi *et al.* (2004) examined the performance of hybrids of DTP across stress (drought and low nitrogen) and unstressed environments. The normal single cross (NSC) hybrids were slightly better than DTP topcrosses under unstressed conditions. However, under stressed conditions NSC hybrids performed very poorly. The NSC hybrids yielded only 3.3–4.8% under drought and 34.8–36.2% under low nitrogen, while DTP hybrids yielded up to 31.8–42.4% under drought and 48.9–63.6% under low nitrogen. Improved performance of DTP hybrids across the environments was related to improvements in secondary traits under stress conditions: reduced ASI, increased ears per plant, delayed senescence and relatively high leaf chlorophyll. Correlation and regression analysis showed a strong relationship between grain yield under drought and low-nitrogen stress in the germplasm improved for mid-season drought tolerance. However, the relationship was not significant with germplasm improved for yield per se under optimal conditions.

The improved sources from CIMMYT exhibited an equally good level of drought tolerance in Southern Africa, and when introgressed in local germplasm, the newly developed hybrids have shown superior and stable performance across the wide range of growing conditions in Southern and eastern Africa. The open-pollinated varieties developed using these source germplasms showed 35% superiority over commercial hybrids under moderate to severe levels of water stress (Banziger *et al.*, 2000b).

Improved drought tolerance using stress-adaptive traits

Several traits for drought and low-nitrogen tolerance in maize were evaluated and their value as a secondary trait assessed (Bolaños and Edmeades, 1996; Banziger *et al.*, 1997), and a few traits with proven value in selection for drought tolerance were used extensively for improving maize productivity under limited moisture conditions.

EARS PER PLANT Drought at flowering causes severe barrenness and destabilizes the grain yield. Ability of a genotype to produce an ear under such adverse conditions is certainly an important characteristic of drought tolerance in maize. More than 75% of the yield variation under drought was accounted for by variation in the number of ears and kernels per plant (Bolaños and Edmeades, 1996; Edmeades *et al.*, 2000). Grain yield under drought stress showed a strong relationship with ears per plant ($r = 0.90 \pm 0.14$) and, across the trials, a strong curvilinear relationship with ears per plant ($r^2 = 0.94^{**}$). Being highly heritable (Bolaños and Edmeades, 1996; Edmeades *et al.*, 2000) and having a stronger relationship with grain yield, ears per plant has been used as a trait in the selection for water-limited environments and is important in the selection index for drought tolerance (Banziger *et al.*, 2000a).

ANTHESIS–SILKING INTERVAL The ASI is a symptom of ear growth rate, and the difference in ASI among genotypes growing in the same environment reflects differences in partitioning efficiency to the ear. The genetic correlation between grain yield and ASI in a diverse array of genotypes grown under drought at flowering is about −0.6 (Bolaños and Edmeades, 1996; Edmeades *et al.*, 2000), and the strong curvilinear relationships observed with yield under severe drought stress suggest that ASI is a visual indicator of underlying processes affecting reproductive success. Recurrent selection for mid-season drought tolerance in several diverse tropical maize populations at CIMMYT over two to ten cycles has increased grain yield under stress by about 100 kg/ha/year and reduced ASI by 0.6 days/year. Reduction in ASI was associated with decline in spikelets per ear, increase in rate of ear growth, spikelets and silk growth, and increase in HI (Edmeades *et al.*, 2000).

LEAF SENESCENCE Studies at CIMMYT revealed little adaptive value of this trait because of lack of association between green leaf area longevity and grain yield and the apparent lack of progress in selecting for delayed senescence (Bolaños *et al.*, 1993). Nevertheless, delayed senescence and stay-green is an important trait under drought stress, indicative of plant water status, and is useful for selection of maize genotypes under drought stress, although relatively less weight is given in the selection index (Banziger *et al.*, 2000a). The stay-green characteristic of maize facilitates a long grain-filling period and a long duration of harvesting in silage varieties (Choi *et al.*, 1995). Bekavac *et al.* (1998) detected highly significant genetic and phenotypic correlations between stay-green, stalk water content, leaf water content, vegetative period and grain moisture in two synthetic maize populations (Syn103NS and Syn140NS), with most consistent genetic correlations established between stay-green and leaf water content ($r = 0.85$–0.90).

TASSEL SIZE The maize plant is a prolific pollen shedder, and a vigorous maize plant can produce

25 million pollen grains, which is much more than required for pollinating the 500–1000 ovules present in a female flower (cob). The tassel has no role to play after completion of pollination. A small-sized tassel is preferred to reduce the sink competition, particularly when there is high competition for limited assimilates under stressed condition. A negative correlation between tassel size and grain yield under drought was observed in tropical maize populations (Bolaños and Edmeades, 1996). Tassel size is a highly heritable trait and can be easily altered by selection (Fischer *et al.*, 1987). Eight cycles of recurrent selection for mid-season drought tolerance resulted in a reduction of (−0.45) primary tassel branches per plant and tassel biomass (−2.6%) per cycle, although the trait was not under direct selection (Bolaños and Edmeades, 1993). In another study, direct selection for reduced tassel branches led to a significant increase in female inflorescence biomass at 50% silking, a reduction in tassel biomass and an increase in HI (Fischer *et al.*, 1987). These findings indicate that reduced tassel size in tropical maize is directly associated with increase in ear growth at flowering and in HI.

Groundnut

The segregating populations, derived from crosses involving known drought-tolerant germplasm and widely adapted high-yielding cultivars, are generation-advanced/evaluated under rainfed conditions at ICRISAT, Patancheru, India. The advanced breeding lines are yield tested in both rainy (rainfed conditions at ICRISAT (Patancheru) and Anantapur, India) and post-rainy (simulated mid-season stress conditions at ICRISAT (Patancheru)) seasons in replicated trials. The promising drought-tolerant varieties identified on the basis of their pod and seed yield, after 3 years of evaluation, are included in the international drought trial, tested by cooperators in Asia and Africa. From such evaluation, we identified ICGVs 87354, 86187 and 86647, which consistently outyielded controls in acute drought-prone areas in India, and ICGV 86635 in Thailand and Indonesia (Reddy *et al.*, 1994). ICGV 87354 has been shown to possess higher T, TE and HI (Rachaputi and Wright, 2003), contributing to its higher performance under water-limiting conditions. Further, simultaneous evaluations for drought tolerance under imposed drought conditions at ICRISAT revealed that ICGSs 11, 37, 44 and 76, ICG (FDRS) 10 and ICGV 86021 are drought tolerant. The first four varieties were released in India, the fifth in India and Myanmar, and the sixth in Indonesia.

Short-duration, high-yielding groundnut cultivars are required for many agroecological situations in the SAT. Using predetermined cumulative thermal time as a basis to select for earliness (Vasudeva Rao *et al.*, 1992), ICRISAT developed several short-duration varieties, with potential to escape terminal drought; some of these varieties have been released for cultivation in some countries (Fig. 8.9).

New breeding approaches utilizing physiological traits have been proposed to improve the understanding and efficiency of selection of superior drought-tolerant genotypes. Variations for T, TE and HI have been reported in groundnut. More recently, it has been shown that the negative association observed between TE and HI can be broken, thus offering scope to combine TE and HI in groundnut for improved yield performance. Interestingly, genotypes involving ICGSs 44 and 76 or ICGVs 86754 and 87354 in their pedigrees, all reported to be tolerant to drought, had superior yield performance because of higher TE and HI or all the three traits, while for the other genotypes, the dominant contribution to the yield was from T and/or HI (Rachaputi and Wright, 2003). There is therefore scope for pyramiding physiological traits associated with drought tolerance into improved genetic background. Yield performance of some of these selected lines was superior even under irrigated conditions (Nigam *et al.*, 2002), indicating that the physiological traits such as TE and HI could be used as a selection criterion for high water productivity under irrigated conditions and in high rainfall areas.

The CIDL and SLA have been identified as surrogate traits associated with TE in groundnut. SLA is a crude but easily measurable parameter, and can be used as a rapid and inexpensive selection criterion for high TE. Further, it has been demonstrated that SPAD chlorophyll metre readings (SCMR) serve as a rapid, low-cost and non-destructive technique to screen large breeding populations for SLA

Fig. 8.9. Drought-tolerant groundnut varieties enhance adaptation to varied cropping systems.

(Nageswara Rao *et al.*, 2001) and specific leaf nitrogen (Madhava *et al.*, 2003). Screening of groundnut germplasm for SLA indicated significant variability within and between taxonomic groups of groundnut. Genotypes belonging to the variety *hypogaea* (Virginia bunch and runner types) had a lower mean SLA than those of variety *fastigiata* (Valencia and Spanish types), suggesting the likelihood of higher TE. However, the former had lower partitioning ability than the latter. Groundnut genotypes with lower SLA (high TE) have shown more stability in dry matter production under drought (Nigam *et al.*, 2002).

Chickpea

One way for the chickpea crop to escape end-of-season drought is to develop varieties with early growth vigour, early flowering and early maturity (Calcagno and Gallo, 1993). Kumar *et al.* (1985) developed an extra-early chickpea, ICCV 2, from a transgressive segregant of a cross involving five chickpea lines (Kumar and Abbo, 2001). A major recessive gene, *efl-1*, responsible for about 3 weeks difference in flowering time has been identified (Kumar and van Rheenen, 2000). A super-early chickpea segregant, ICCV 96029, which flowers about a week earlier than either of the parents, was selected from a cross involving two extra-early varieties (Kumar and Rao, 1996). These early-flowering genotypes will be useful in combining earliness with other drought-tolerance traits to develop genotypes with stable yields.

Pigeonpea

Short- and extra-short-duration pigeonpea

Pigeonpea in India is traditionally grown during the rainy season (180–270 days duration) as an intercrop. However, since the late 1970s it has been shown that genotypes of shorter duration (120–150 days), when grown during the rainy season, can give yields similar to, or even higher than, long-duration genotypes in northern India (Saxena and Yadav, 1975). In Australia, properly managed photoperiod-insensitive genotypes could produce grains up to 8.8 t/ha (Wallis *et al.*, 1983). The development and release of short-duration pigeonpea varieties that mature in about 120 days has helped the expansion of the crop to newer areas (Singh *et al.*, 1990). These varieties are relatively insensitive to photoperiod and show high per day productivity.

Pigeonpea hybrids

The world's first pigeonpea hybrid (ICPH 8), based on genetic male sterility, was released in 1991 for cultivation in India, with 20–34% yield advantage (Saxena, 2002). ICPH 8 also showed drought, disease and waterlogging tolerance (Saxena *et al.*, 1996). Further, using short-duration male sterile lines (Reddy *et al.*, 1995), the Indian programme released five short-duration hybrids (COPH 1, COPH 2, PPH, AKPH 2022 and AKPH 4104), with 11–64% yield advantage over the controls (Saxena, 2002). These hybrids have revealed a higher seedling vigour, crop growth rate and pod/seed density, and higher plasticity with no yield reduction at suboptimal population levels compared with controls (Fig. 8.10) (Saxena *et al.*, 1992).

Enhancing Drought Tolerance Using Biotechnological Tools

Introgression breeding using wild relatives

Wild relatives of groundnut, chickpea and pigeonpea are endowed with important traits necessary for the improvement of the three legumes: *Arachis glabrata*, *Arachis cardenasii* and *Arachis pintoi* in groundnut with multiple resistance to drought, diseases and insects (Fisher and Cruz, 1994); *Cicer stapfianum*, *Cicer subaphyllum* and *Cicer pungens* in chickpea with drought tolerance and deep root system (van der Maesen, the Netherlands, personal communication); and *Cajanus acutifolius* and *Cajanus confertiflorus* in pigeonpea with silvery hairs, which confer drought tolerance (van der Maesen, 1986). Some of the above wild species are cross compatible with their respective cultigens, and work is in progress at ICRISAT to introgress drought-tolerance traits into improved genetic background in these legumes. An interspecific derivative in chickpea, BG 1103 (renamed as Pusa 1103), has been released for cultivation in northern India because of its high yield and tolerance to fusarium wilt and drought (Abbo *et al.*, 2007).

Marker-aided introgression of QTL associated with drought tolerance

Pearl millet

Linkage groups (LG) 2, 4 and 6 are reported to harbour several QTLs associated with drought tolerance, flowering, stover and grain yield, panicle numbers, HI, and panicle HI, with some common QTL across stress environments and tester backgrounds (Yadav *et al.*, 2002, 2003,

Fig. 8.10. Hybrid pigeonpea cultivars have shown better drought tolerance.

2004). Bidinger *et al.* (2005) demonstrated that QTL-based hybrids outyielded under stress but with yield penalty under non-stress environments. More recently, Bidinger *et al.* (2007) identified three QTLs as primary candidates for marker-assisted selection (MAS) for improved grain yield across variable post-flowering moisture environments. The QTLs on LG2 and LG3 also co-mapped with QTLs for HI across environments for grain numbers and individual grain mass under severe terminal stress. Neither had a significant QTL × environment interaction, indicating their predictive effects should occur across a broad range of available moisture environments. ICRISAT has initiated a large-scale marker-aided breeding programme to enhance post-flowering drought tolerance in pearl millet.

Sorghum

An integrated, interactive sorghum linkage map based on all available published information, incorporating RFLP (restriction fragment length polymorphism) and SSR (simple sequence repeat) marker locus positions as well as approximate map positions of stay-green QTLs, has been developed and made available globally (www.icrisat.org). Post-flowering drought in sorghum is associated with the stay-green phenotype. Xu *et al.* (2000) reported several QTLs with large effects for stay-green and chlorophyll content under post-flowering drought-stress environments; few QTLs for stay-green coincided with the chlorophyll content QTL. Some of the sorghum stay-green QTLs also corresponded with stay-green QTLs in maize and were congruent with other drought-related traits in maize and rice (Kebede *et al.*, 2001). More recently, Harris *et al.* (2007) demonstrated that some of the sorghum stay-green QTLs individually reduced post-flowering drought-induced leaf senescence when near-isogenic lines (NIL) containing individual QTLs were evaluated under drought-stress environments. ICRISAT initiated marker-assisted backcross to transfer stay-green QTLs with major effects from stay-green donors (B35 and E 36–1) into a range of diverse genotypes from Asia, Africa and Latin America (Fig. 8.11). Thus there is now an opportunity to assess the efficacy of marker-assisted backcrossing for this trait, which can be scored phenotypically only under conditions of terminal drought stress.

Fig. 8.11. Expression of stay-green trait (in sorghum) under receding soil moisture conditions in a vertisol.

Maize

Large numbers of QTLs associated with grain yield, yield components, and for secondary traits such as ears per plant, ASI and leaf abscisic acid concentration (L-ABA) have been reported in maize under different water regimes including severe drought stress. QTLs for leaf growth co-localized with QTLs for ASI (Welcker *et al.*, 2007). QTLs for seminal root growth co-localized with QTLs for grain yield and drought tolerance index (Tuberosa *et al.*, 2002). Giuliani *et al.* (2005) field evaluated near-isogenic hybrids containing a major QTL for L-ABA for 2 years under well-watered and water-stressed conditions. They reported that the QTL allele for high L-ABA markedly reduced stomatal conductance and root lodging. Across water regimes, the QTL confirmed its effect on L-ABA and showed a concurrent effect on root angle, branching, number, diameter and dry weight. This QTL affects root lodging through a constitutive effect on root architecture. Landi *et al.*

(2005) validated a major QTL for L-ABA that affects root traits and relative water content. Tuberosa *et al.* (2003) reported several chromosome regions affecting root traits and grain yield under well-watered and/or drought-stressed conditions, with most important QTL effects on few chromosome bins. Two QTLs with major effects on yield and stay-green under post-flowering drought had pleotropic effects on yield under non-stressed conditions (Sari-Gorla *et al.*, 1999).

More recently, Ribaut and Ragot (2007) demonstrated that introgression of favourable alleles at five target regions, involved in the expression of yield components and flowering traits, increased grain yield and reduced the asynchrony between male and female flowering under water-limited conditions. They recovered 85% of the recurrent parent's genotype at non-target loci only in four generations of marker-assisted backcrossing (MABC) by screening large segregating populations for three of the four generations. Mean grain yield of MABC-derived hybrids was consistently higher than that of control hybrids under severe water stress. Under those conditions, the best five MABC-hybrids yielded, on average, at least 50% more than the control hybrids. However, under mild stress, defined as resulting in <50% yield reduction, no difference was observed between MABC-derived hybrids and the control hybrids, confirming that genetic regulation for drought tolerance is dependent on stress intensity.

Groundnut

Krishnamurthy *et al.* (2007) evaluated TE in a set of 318 RILs, derived from a cross between a high TE (ICGV 86031) and a low TE (TAG24) parent, using SLA, SCMR and carbon isotope discrimination (δ^{13}) as surrogate of TE under progressive soil drying in a pot culture. Large and consistent variation exists for TE in this population; however, surrogate traits turned out to relate little (r <0.13–0.15) with TE. New sources of drought tolerance have been identified, which need to be further assessed for drought-tolerance traits. A new set of SSR markers has been generated, which is currently being assessed to identify genetically diverse, drought-tolerant parents for developing new mapping populations.

Chickpea

Research efforts have been made at ICRISAT to characterize and map QTLs associated with drought-avoidance root traits. RILs involving ICC 4958 (a genotype with large roots) and Annigeri, when evaluated under terminal drought conditions, showed large variations for rooting depth and root biomass at 35 days after sowing, shoot biomass and seed yield at maturity, and partitioning. However, no direct relationship between seed yield and root depth or root biomass could be established from this study, probably owing to moderate drought intensity observed during the crop season. The root-trait benefits on the yield were clearly shown to be visible in environments with a productivity level of <1.0 t/ha (Saxena, 1987).

New sources of genetic variation, ICCs 1431, 8350, 15697, 3512 and 11498, with deep root traits and drought tolerance have been identified (Kashiwagi *et al.*, 2005). New mapping populations involving ICC 8261 and ICC 4958 (large root) with ICC 283 and ICC 1882 (small root) have been developed, and the F_1, F_2, BC_1 and BC_2 populations are being analysed for the estimation of genetic components and evaluated for root traits and field agronomic performance. A large number of SSR markers are now available to genotype these populations using ABI3700 at ICRISAT. A major QTL contributing to one-third of variation for root length and root biomass has been identified (Chandra *et al.*, 2004).

Association mapping

Conventional linkage mapping for identification of trait markers relies on the development of defined genetic populations: NILs, RILs and advanced backcross derivatives. The development of such populations takes several years and is expensive, and the resultant markers must be validated in diverse populations before application in breeding programmes. Therefore, there has been considerable interest in the development of methodologies that do not require the creation of mapping populations and generate markers that can be more immediately applied in diverse breeding programmes. Linkage disequilibrium analysis is an alternative means of identifying a close association between trait (such as drought tolerance) and marker loci. It relies on population-level associations among alleles at trait loci and those at nearby markers. Such associations typically arise when all or most of the trait alleles in a population share a common ancestral origin. This approach is based on the use of natural populations rather than genetic populations, which has the added advantage that the resultant marker tends to be both genetically and physically close to the gene of interest and, therefore, more readily applied in a diverse range of breeding programmes. Marker-trait association using this approach has been established in crop plants (Dwivedi *et al.*, 2007b). However, this approach has its own limitation with respect to population structure, which needs to be taken care of to avoid false discovery.

Transgenic

Maize

AtNF-YB1, a transcription factor from the nuclear factor Y (NF-Y) family, confers improved performance in *Arabidopsis* under drought conditions. Nelson *et al.* (2007) identified maize homologues (ZmNF-YB2) of AtNF-YB1, which they used to transform inbred elite maize. The transgenic maize plants constitutively expressing ZmNF-YB2 showed less leaf rolling, cooler leaf temperature and a higher chlorophyll index, photosynthetic rate and stomatal conductance; all these stress-adaptive traits contributed to grain yield advantage under water-limited environments. The best-performing transgenic lines produced about 50% increase in grain yield relative to the irrigated control. Qin *et al.* (2007) isolated *ZmDREB2A*, a *DREB2* homologue from maize, which is induced in response to cold, drought, salt and heat stresses in seedlings. Maize transgenic lines with *ZmDREB2A* improved drought and heat-stress tolerance, which could be due to induction of late embryogenesis abundant protein (LEA), heat shock and detoxification genes.

Glycine betaine plays an important role in confering abiotic stress tolerance in some plants including maize. Quan *et al.* (2004) transformed a maize inbred line with the beta gene from *Escherichia coli* encoding choline dehydrogenase, a key enzyme in the biosynthesis of glycine betaine from choline. The transgenic plants accumulated higher levels of glycine betaine, were more tolerant to drought, and produced significantly higher grain yield than wild-type plants after drought treatment. The enhanced glycine betaine accumulation in transgenic plants provides greater protection of the integrity of the cell membrane and greater activity of enzymes compared with wild-type plants under drought stress.

Groundnut

Water use efficiency under drought conditions is one of the promising traits to improve and stabilize crop yields under drought conditions. The recent work at ICRISAT revealed that when a popular groundnut cultivar, JL 24, was introduced with *DREB1A* from *Arabidopsis* (through *Agrobacterium tumefaciens*), driven by the stress-inducible promoter *rd29A*, the transgenic plants did not show growth retardation. When T3 progenies were exposed to progressive soil drying in a pot-culture experiment, all the transgenic plants were able to maintain a transpiration rate equivalent to the well-watered control in soil dry enough to reduce the transpiration rate in wild-type JL 24, with most of these plants achieving higher TE. One of the plants under water-limited conditions showed 40% higher TE than the wild-type JL 24 (Bhatnagar-Mathur *et al.*, 2007). Vadez *et al.* (2007) reported that *DREB1A* seems to be involved in the development of groundnut roots under drought conditions, as they noted excessive root growth in transgenic plants whereas roots remained unchanged in wild-type JL 24, which resulted in higher water uptake from the soil.

Conclusion

Globally, the five ICRISAT crops and rainfed maize play a predominant role in enhancing the rural livelihood opportunities in arid and semi-arid regions, which experience acute water shortage. A combination of approaches has been employed to enhance the adaptation of these crops under drought conditions. These include matching the genotypes to the environment, developing short-duration varieties, selecting for stable yield and wide adaptability, screening and breeding under water-limiting environments and/or imposed stress conditions, and employing cultivar options (varieties versus hybrids). However, these approaches have resulted in moderate success in breeding cultivars that have given enhanced water productivity under drought conditions.

Recently, a more focused research on drought has enabled researchers to identify simple and effective traits associated with drought tolerance. For example, panicle HI and individual grain mass in pearl millet; glossy and stay-green in sorghum; deep root in chickpea; T, TE and HI in groundnut; and ASI, ears per plant, leaf senescence and tassel size in maize. Using these approaches, several genetically enhanced products have been developed, some of which have reached the farmers' fields.

Recent advances in genome mapping have enabled researchers to apply DNA markers technology to dissect the genetic structure of the germplasm collection, identify QTLs associated with drought-tolerance traits, and apply MAS in combination with conventional breeding to enhance drought tolerance in these crops. Products of MAS in pearl millet and maize have conclusively shown superior performance under severe drought-stress conditions, but no advantage under mild drought stress or under well-watered conditions. Genetically transformed groundnut with the *DREB1A* gene driven by the stress-inducible promoter *rd29A* has shown promise in enhancing drought tolerance, with no symptoms of growth retardation. Transgenic maize containing ZmNF-YB2 or *ZmDREB2A* has contributed to enhanced drought tolerance and/or grain yield advantage under drought-stress conditions. A combination of approaches (trait-based selection, QTLs and transgene) needs to be deployed to support the empirical approach in order to enhance drought tolerance in these crops.

References

Abbo, S., Redden, R.J. and Yadav, S.S. (2007) Utilization of wild relatives. In: Yadav, S.S., Redden, R.J., Chen, W. and Sharma, B. (eds) *Chickpea Breeding and Management*. CAB International, Wallingford, UK, pp. 338–368.

Acevedo, E. and Ferreres, E. (1993) Resistances to abiotic stresses. In: Hayward, M.D., Bosemark, N.O. and Romagosa, I. (eds) *Plant Breeding: Principles and Prospects*. Chapman and Hall, London, UK, pp. 406–421.

Banziger, M., Betran, F.J. and Lafitte, H.R. (1997) Efficiency of high nitrogen selection environments for improving maize for low nitrogen target environment. *Crop Science* 37, 1103–1109.

Banziger, M., Edmeades, G.O., Beck, D. and Bellon, M. (2000a) Breeding for drought and nitrogen stress tolerance in maize. From theory to practice. CIMMYT, Mexico.

Banziger, M., Mugo, S. and Edmeades, G.O. (2000b) Breeding for drought tolerance in tropical maize – conventional approaches and challenges to molecular approaches. In: Ribaut, J.M. and Poland, D. (eds) *Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-limited Environments*. CIMMYT, El Batan, Mexico, pp. 69–72.

Banziger, M., Pixley, K.V., Vivek, B. and Zambezi, B.T. (2000c) Characterization of elite maize germplasm grown in eastern and southern Africa: results of the 1999 regional trials conducted by CIMMYT and the Maize and Wheat Improvement Research Network for SADC. CIMMYT, Harare, Zimbabwe, pp. 1–44.

Bekavac, G., Stojakovic, M., Jockovic, D., Bocanski, J. and Purar, B. (1998) Path analysis of stay-green trait in maize. *Cereal Research Communications* 26, 161–167.

Bhatnagar-Mathur, P., Devi, M.J., Reddy, D.S., Lavanya, M., Vadez, V., Serraj, R., Yamaguchi-Shinozaki, K. and Sharma, K.K. (2007) Stress-inducible expression of At *DREB1A* in transgenic groundnut (*Arachis hypogaea* L.) increases transpiration efficiency under water limiting conditions. *Plant Cell Reports* 26, 2071–2082.

Bidinger, F.R. and Mukuru, S.Z. (1995) Threshing percentage as an indicator of terminal drought stress in sorghum. In: Mukuru, S.Z. and King, S.B. (eds) *Eighth EARSAM Regional Workshop on Sorghum and Millets*, 30 Oct–5 Nov 1992, Wad Medani, Sudan. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 27–35.

Bidinger, F.R., Mahalakshmi, V., Talukdar, B.S. and Alagarswamy, G. (1982) Improvement of drought resistance in pearl millet. In: *Drought Resistance in Crops with Emphasis on Rice*. International Rice Research Institute (IRRI), Los Baños, Philippines. pp. 357–375.

Bidinger, F.R., Mahalakshmi, V. and Rao, G.D.P. (1987a) Assessment of drought resistance in pearl millet (*Pennisetum americanum* (L.) Leeke). I. Factors affecting yields under stress. *Australian Journal of Agricultural Research* 38, 37–48.

Bidinger, F.R., Mahalakshmi, V. and Rao, G.D.P. (1987b) Assessment of drought resistance in pearl millet (*Pennisetum americanum* (L.) Leeke). II. Estimation of genotype response to stress. *Australian Journal of Agricultural Research* 38(1), 49–59.

Bidinger, F.R., Hammer, G.L. and Muchow, R.C. (1996) The physiological basis of genotype by environment interaction in crop adaptation. In: Cooper, M. and Hammer, G.L. (eds) *Plant Adaptation and Crop Improvement*. CAB International, Wallingford, UK, pp. 329–347.

Bidinger, F.R., Chandra, S. and Mahalakshmi, V. (2000) Genetic improvement of tolerance to terminal drought stress in pearl millet (*Pennisetum glaucum* (L) R. Br.) In: Ribaut, J.M. and Poland, D. (eds) *Molecular Approaches for the Genetic Improvement of Cereals for Stable Production in Water-limited Environments*. CIMMYT, El Batan, Mexico, pp. 59–63.

Bidinger, F.R., Serraj, R., Rizvi, S.M.H., Howarth, C.J., Yadav, R.S. and Hash, C.T. (2005) Field evaluation of drought tolerance QTL effects on phenotype and adaptation in pearl millet (*Pennisetum glaucum* (L.) R. Br.) topcross hybrids. *Field Crops Research* 94, 14–32.

Bidinger, F.R., Napolean, T., Hash, C.T., Yadav, R.S. and Howarth, C.J. (2007) Quantitative trait loci for grain yield in pearl millet under variable post-flowering moisture conditions. *Crop Science* 47, 969–980.

Bieler, P., Fussel, L.K. and Bidinger, F.R. (1993) Grain growth of *Pennisetum glaucum* (L.) R. Br. under well-watered and drought-stressed conditions. *Field Crops Research* 31, 41–54.

Blum, A., Jordan, W.R. and Arkin, G.F. (1977) Sorghum root morphogenesis and growth. II. Manifestation of heterosis. *Crop Science* 17, 153–157.

Bolaños, J. and Edmeades, G.O. (1993) Eight cycles of selection for drought tolerance in lowland tropical maize. II. Responses in reproductive behaviour. *Field Crops Research* 31, 253–268.

Bolaños, J. and Edmeades, G.O. (1996) The importance of the anthesis-silking interval in breeding for drought tolerance in tropical maize. *Field Crops Research* 48, 65–80.

Bolaños, J., Edmeades, G.O. and Martinez, L. (1993) Eight cycles of selection for drought tolerance in lowland tropical maize. III. Response in drought-adaptive physiological and morphological traits. *Field Crops Research* 31, 269–286.

Boote, K.J., Varnell, R.J. and Duncan, W.G. (1976) Relationships of size, osmotic concentration, and sugar concentration of groundnut pods to soil water. *Proceedings of Crop and Soil Science Society*, Florida 35, 47–50.

Boote, K.J., Stansell, J.R., Schubert, A.M. and Stone, J.T. (1982) Irrigation, water use, and water relations. In: Pattee, H.E. and Young, C.T. (eds) *Peanut Science and Technology*. American Peanut Research Education Society, Yoakum, Texas, USA, pp. 164–205.

Borrell, A.K. and Douglas, A.C.L. (1996) Maintaining green leaf area in grain sorghum increases yield in a water-limited environment. Third Australian Sorghum Conference, Tamworth, Melbourne. Occasional Publication No. 93, pp. 315–322.

Bruce, W.B., Edmeades, G.O. and Baker, T.C. (2002) Molecular and physiological approach to maize improvement for drought tolerance. *Journal of Experimental Botany* 53, 13–25.

Byrne, P.F., Bolaños, J., Edmeades, G.O. and Eaton, D.L. (1995) Gains from selection under drought versus multilocation testing in related tropical maize populations. *Crop Science* 35, 63–69.

Calcagno, F. and Gallo, G. (1993) Physiological and morphological basis of abiotic stress resistance in chickpea. In: Singh, K.B. and Saxena, M.C. (eds) *Breeding for Stress Tolerance in Cool Season Food Legumes*. John Wiley & Sons and Sayce Publishing, London, pp. 293–309.

Castleberry, R.M., Crum, C.W. and Krull, C.F. (1984) Genetic improvements of US maize cultivars under varying fertility and climatic environments. *Crop Science* 24, 33–36.

Chandra, S., Buhariwalla, H.K., Kashiwagi, J., Harikrishna, S., Sridevi, K.R., Krishnamurthy, L., Serraj, R. and Crouch, J.H. (2004) Identifying QTL-linked markers in marker-deficient crops. In: *Proceedings of Fourth International Crop Science Congress*, Brisbane, Australia. http://www.cropscience.org.au/icsc2004/poster/3/4/1/795_chandras.htm

Chapman, S.C., Cooper, M., Hammer, G.L. and Butler, D.G. (2000) Genotype by environment interactions affecting grain sorghum. II. Frequencies of different seasonal patterns of drought stress are related to location effects on hybrid yields. *Australian Journal of Agricultural Research* 51, 209–221.

Chauhan, Y.S., Saxena, N.P. and Johansen, C. (1992) Abiotic factors limiting chickpea and pigeonpea production. In: Sachan, J.N. (ed.) *Proceedings of National Symposium on New Frontiers in Pulses Research and Development*. Directorate of Pulses Research, Kanpur, India, pp. 111–123.

Chauhan, Y.S., Johansen, C. and Singh, L. (1993) Adaptation of extra short duration pigeonpea to rainfed semi-arid envirionments. *Experimental Agriculture* 29, 233–243.

Chauhan, Y.S., Silim, S.N., Rao, J. and Johansen, C. (1997) A pot technique to screen pigeonpea cultivars for resistance to waterlogging. *Journal of Agronomy and Crop Science* 178, 179–183.

Chauhan, Y.S., Wallace, D.H., Johansen, C. and Singh, L. (1998) Genotype by environment interaction effect on yield and its physiological basis in short duration pigeonpea. *Field Crops Research* 59, 141–150.

Choi, K.J., Chin, M.S., Park, K.Y., Lee, H.S., Seo, J.H. and Song, D.Y. (1995) Heterosis and heritability of stay-green characters. *Maize Genetics Cooperative Newsletter* 69, 122–123.

Cooper, M. and DeLacy, I.H. (1994) Relationships among analytical methods used to study genotypic variation and genotype by environment interaction in plant breeding multi-environment experiments. *Theoretical and Applied Genetics* 88, 561–572.

Duvick, D.N. (1995) Biodiversity, carrying capacity and people. In: Annual Meeting. American Association for Advancement in Science, Atlanta, Georgia, USA.

Dwivedi, S.L., Bertioli, D.J., Crouch, J.H., Valls, J.E., Upadhyaya, H.D., Fávero, A., Moretzsohn, M. and Paterson, A. (2007a) Peanut. In: Kole, C. (ed.) *Genome Mapping and Molecular Breeding in Plants*, Vol. 2. Springer-Verlag, Berlin, Germany, pp. 115–151.

Dwivedi, S.L., Crouch, J.H., Mackill, D.J., Xu, Y., Blair, M.W., Ragot, M., Upadhyaya, H.D. and Ortiz. R. (2007b) The molecularization of public sector crop breeding: progress, problems, and prospects. *Advances in Agronomy* 95, 163–318.

Edmeades, G.O., Chapman, S.C. and Lafitte, H.R. (1994) Photoperiod sensitivity of tropical maize cultivars is reduced by cool night temperatures. Presented at the 86th Annual Meeting of the American Society of Agronomy, Seattle. USA.

Edmeades, G.O., Banziger, M., Chapman, S.C., Ribaut, J.M. and Bolaños, J. (1995) Recent advances in breeding for drought tolerance in maize. Presented at the West and Central Africa Regional Maize and Cassava Workshop, Cotonou, Republic of Benin.

Edmeades, G.O., Bolaños, J., Banziger, M., Ribaut, J.M., White, J.W., Reynolds, M.P. and Lafitte, H.R. (1998) Improving crop yields under water deficits in the tropics. In: Chopra, V.L., Singh, R.B. and Varma, A. (eds) *Crop Productivity and Sustainability – Shaping the Future*. Proceedings of 2nd International Crop Science Congress, Oxford and IBH, New Delhi, India, pp. 437–451.

Edmeades, G.O., Bolaños, J., Elings, A., Ribaut, J.M., Banziger, M. and Westgate, M.E. (2000) The role and regulation of the anthesis-silking interval in maize. In: Westgate, M.E. and Boote, K.J. (eds) *Physiology and Modeling Kernel Set in Maize*. CSSA Special Publication No. 29. Madison, Wisconsin, USA, pp. 43–73.

Fischer, K.S., Edmeades, G.O. and Johnson, E.C. (1987) Recurrent selection for reduced tassel branches number and reduced leaf area density above the ear in tropical maize populations. *Crop Science* 27, 1150–1156.

Fisher, M.J. and Cruz, P. (1994) Some ecophysiological aspects of *Arachis pintoi*. In: Kerridge, P.C. and Hardy, B. (eds) *Biology and Agronomy of Forage Arachis*. CIAT, Cali, Columbia, pp. 53–70.

Fisher, R.A. and Maurer, R. (1978) Drought resistance in spring wheat cultivars. 1. Grain yield response. *Australian Journal of Agricultural Research* 29, 897–912.

Fussell, L.K., Craig, J., Pearson, J. and Norman, M.J.T. (1980) Effect of temperature during various growth stages on grain development and yield of *Pennisetum americanum*. *Journal of Experimental Botany* 31, 621–633.

Fussell, L.K., Bidinger, F.R. and Bieler, P. (1991) Crop physiology and breeding for drought tolerance: research and development. *Field Crops Research* 27, 183–199.

Gibbons, R.W. (1978) Adaptation and utilization of groundnuts in different environments and farming systems. In: Summerfield, R.J. and Bunting, H. (eds) *Advances in Legume Sciences*. Royal Botanical Gardens, Kew, UK, pp. 483–493.

Giuliani, S., Sanguineti, M.C., Tuberosa, R., Bellotti, M., Salvi, S. and Landi, P. (2005) *Root-ABA1*, a major constitutive QTL, affects maize root architecture and leaf ABA concentration at different water regimes. *Journal of Experimental Botany* 56, 3061–3070.

Gupta, S.C., Johansen, C. and Singh, L. (1989) Uniformity of nomenclature in short duration pigeonpeas. *International Pigeonpea News* 10, 3–6.

Hammer, G.L. and Muchow, R.C. (1994) Assessing climatic risk to sorghum production in water-limited subtropical environments. 1. Development and testing of a simulation model. *Field Crops Research* 36, 221–234.

Hanks, R.J., Keller, J., Rasmussen, V.P. and Wilson, G.D. (1976). Line-source sprinkler for continuous variable irrigation crops production studies. *Soil Science Society of America Journal* 40, 426–429.

Harris, D., Mathews, R.B., Nageswara Rao, R.C. and Williams, J.H. (1988) The physiological basis for yield differences between four groundnut genotypes in response to drought. III. Developmental processes. *Experimental Agriculture* 24, 215–226.

Harris, K., Subudhi, P.K., Borrell, A., Jordan, D., Rosenow, D., Nguyen, H., Klein, P., Klein, R. and Mullet, J. (2007) Sorghum stay-green QTL individually reduce post-flowering drought induced leaf senescence. *Journal of Experimental Botany* 58, 327–338.

Henson, I.E., Mahalakshmi, V., Alagarswamy, G. and Bidinger, F.R. (1984) The effect of flowering on stomatal response to water stress in pearl millet (*Pennisetum americanum* (L.) Leeke). *Journal of Experimental Botany* 35, 219–226.

Henzell, R.G., Brengman, R.L., Fletcher, D.S. and McCosker, A.N. (1992) Relationship between yield and non-senescence (stay-green) in some grain sorghum hybrids grown under terminal drought stress. In: Foale, M.A., Henzell, R.G. and Vance, P.N. (eds) *Proceedings of 2nd Australian Sorghum Conference*, Gatton, Melbourne, Australia. Occasional Publication No. 68. Australian Institute of Agricultural Science, Melbourne, Australia, pp. 355–358.

Henzell, R.G., Hammar, G.I., Borrell, A.K., McIntyre, C.L. and Chapman, S.C. (1997) Research on drought resistance in grain sorghum in Australia. *International Sorghum Millets Newsletter* 38, 1–8.

House, L.R., Verma, B.N., Ejeta, G., Rana, B.S., Kapran, I., Obilana, A.B. and Reddy, B.V.S. (1997) Developing countries breeding and potential of hybrid breeding. In: *Proceedings of International Conference on Genetic Improvement of Sorghum and Pearl Millet*, INTSORMIL, Lubbock, Texas, USA; and ICRISAT, India, pp. 84–96.

Hubick, K.T., Shorter, R. and Farquhar, G.D. (1988) Heritability and genotype × environmental interactions of carbon isotope discrimination and transpiration efficiency in groundnut (*Arachis hypogaea* L.). *Australian Journal of Plant Physiology* 15, 799–813.

Hui, J., Wei, X., Xu, Y.L. and Lin, E. (2005) Impacts of climate change on wheat yield in China. *Acta Agronomy Sinica* 31, 1340–1343.

Johansen, C. (2003) An overview of prospects for genetic enhancement of drought resistance in pigeonpea. In: Saxena, N.P. (ed.) *Management of Agricultural Drought: Agronomic and Genetic Options*. Oxford & IBH Publishing Co., New Delhi, India, pp. 143–150.

Johansen, C., Baldev, B., Brouwer, J.B., Erskine, W.B., Jermyn, W.A., Lang, L.J., Malik, B.A., Miah, A.A. and Silim, S.N. (1994) Biotic and abiotic stresses constraining productivity of cool season food legumes in Asia, Africa and Oceania. In: Muehlbauer, F.J. and Kaiser, W.J. (eds) *Expanding the Production and Use of Cool Season Food Legumes*. Kluwer Academic Publishers, Dordrecht, the Netherlands, pp. 175–194.

Jones, P.G. and Thornton, P.K. (2003) The potential impact of climate change on maize production in Africa and Latin America in 2055. *Global Environmental Change* 13, 51–59.

Kashiwagi, J., Krishnamurthy, L., Upadhyaya, H.D., Krishna, H., Chandra, S., Vadez, V. and Serraj, R. (2005) Genetic variability for drought-avoidance root traits in the mini core germplasm collection of chickpea (*Cicer arietinum* L.). *Euphytica* 146, 213–222.

Kashiwagi, J., Krishnamurthy, L., Singh, S. and Upadhyaya, H.D. (2006) Variation of SPAD chlorophyll meter readings (SCMR) in the mini core germplasm collection of chickpea. *Journal of SAT Agricultural Research* 2, http://www.icrisat.org/journal/cropimprovement/v2i1/v2i1variationof.pdf

Kebede, Y. and Menkir, A. (1987) Sorghum improvement for the moisture stress regions of Ethiopia. In: Menyonga, J.N., Bezuneh, T. and Youdeowei, A. (eds) *Food Grain Production in Semi-Arid Africa*. Proceedings of International Drought Symposium, Nairobi, Kenya, pp. 131–139.

Kebede, H., Subudhi, P.K., Rosenow, D.T. and Nguyen, H.T. (2001) Quantitative trait loci influencing drought tolerance in grain sorghum (*Sorghum bicolor* L. Moench). *Theoretical and Applied Genetics* 103, 266–276.

Ketring, D.L. (1984) Root diversity among groundnut genotypes. *Crop Science* 24, 229–232.

Krishnamurthy, L., Vadez, V., Devi, M.J., Serraj, R., Nigam, S.N., Sheshshayee, M.S., Chandra, S. and Aruna, R. (2007) Variation in transpiration efficiency and its related traits in a groundnut (*Arachis hypogaea* L.) mapping population. *Field Crops Research* 103, 189–197.

Kumar, J. and Abbo, S. (2001) Genetics of flowering time in chickpea and its bearing on productivity in semi-arid environments. *Advances in Agronomy* 72, 107–138.

Kumar, J. and Rao, B.V. (1996) Super-early chickpea developed at ICRISAT Asia Center. *International Chickpea and Pigeonpea Newsletter* 3, 17–18.

Kumar, J. and van Rheenen, H.A. (2000) A major gene for time of flowering in chickpea. *Journal of Heredity* 91, 67–68.

Kumar, J., Haware, M.P. and Smithson, J.B. (1985) Registration of four short duration, fusarium wilt-resistant kabuli (Garbanzo) chickpea germplasms. *Crop Science* 25, 576–577.

Kumar, J., Sethi, S.C., Johansen, C., Kelley, T.G., Rahman, M.M. and van Rheenen, H.A. (1996). Potential of short-duration chickpea varieties. *Indian Journal of Dryland Agricultural Research* 11, 28–32.

Landi, P., Sanguineti, M.C., Salvi, S., Giuliani, S., Bellotti, M., Maccaferri, M., Conti, S. and Tuberosa, R. (2005) Validation and characterization of a major QTL affecting leaf ABA concentration in maize. *Molecular Breeding* 15, 291–303.

Lopez, F.B., Chauhan, Y.S. and Johansen, C. (1997) Effects of timing of drought stress on leaf area development and canopy light interception of short-duration pigeonpea. *Journal of Agronomy and Crop Science* 178, 1–7.

Luo, Q.Y., Bellotti, W., Williams, M. and Bryan, B. (2005) Potential impact of climate change on wheat yields in South Australia. *Agricultural Forest Meteorology* 132, 273–285.

Madhava, H.B., Sheshshayee, M.S., Shankar, A.G., Prasad, T.G. and Udayakumar, M. (2003) Use of SPAD chlorophyll meter to assess transpiration efficiency of groundnut. In: Cruickshank, A.W., Rachaputi, N.C., Wright, G.C. and Nigam, S.N. (eds) *Breeding of Drought-resistant Peanuts*. Proceedings of Collaborative Review Meeting, Hyderabad, India. ACIAR Proceedings No. 112. ACIAR, Canberra, Australia, pp. 3–9.

Mahalakshmi, V. and Bidinger, F.R. (1985) Water stress and time of floral initiation in pearl millet. *Journal of Agricultural Science, Cambridge* 105, 436–445.

Mahalakshmi, V. and Bidinger, F.R. (2002) Evaluation of stay-green sorghum germplasm lines at ICRISAT. *Crop Science* 42, 965–974.

Mahalakshmi, V., Bidinger, F.R. and Raju, D.S. (1987) Effect of timing deficit on pearl millet (*Pennisetum americanum*). *Field Crops Research* 15, 327–339.

Mahalakshmi, V., Bidinger, F.R. and Rao, G.D.P. (1988) Timing and intensity of water deficits during flowering and grain-filling in pearl millet. *Agronomy Journal* 80, 130–135.

Mahalakshmi, V., Bidinger, F.R. and Rao, G.D.P. (1990) Line-source versus irrigated/non irrigated treatments for evaluation of genotype drought response. *Agronomy Journal* 82, 841–844.

Mahalakshmi, V., Monyo, E.S., Payne, W., Quattara, S. and Bidinger, F.R. (1997) Breeding pearl millet for drought tolerance. In: *Proceedings of International Conference on Genetic Improvement of Sorghum and Pearl Millet*. INTSORMIL, Lubbock, Texas, USA; and ICRISAT, India, pp. 443–457.

Maiti, R.K. (1996) *Sorghum Science*. Science Publishers, Inc., Lebanon, New Hampshire, USA.

Maiti, R.K., Prasada Rao, K.E., Raju, P.S. and House, L.R. (1984) The glossy trait in sorghum. Its characteristics and significance in crop improvement. *Field Crops Research* 9, 279–289.

Martinez-Barajas, E., Villnueva-Verduzco, C., Molina-Galan, J., Loza-Tavera, H. and Sanchez-de-Jimenez, E. (1992) Relation of rubisco to maize grain improvement: effect of water restriction. *Crop Science* 32, 718–722.

McCully, M.E. (1999) Roots in soil: unearthing the complexities of roots and their rhizospheres. *Annual Review of Plant Physiology and Plant Molecular Biology* 50, 695–718.

Nageswara Rao, R.C. and Nigam, S.N. (2003) Genetic options for drought management in groundnut. In: Saxena, N.P. (ed.) *Management of Agricultural Drought – Agronomic and Genetic Options*. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India, pp. 123–141.

Nageswara Rao, R.C., Williams, J.H., Sivakumar, M.V.K. and Wadia, K.D.R. (1988) Effect of water deficit at different growth phases of groundnut. II. Response to drought during preflowering phase. *Agronomy Journal* 80, 431–438.

Nageswara Rao, R.C., Williams, J.H., Wadia, K.D.R., Hubick, K.T. and Farquhar, G.D. (1993) Crop growth, water use-efficiency, and carbon isotope discrimination in groundnut (*Arachis hypogaea* L.) genotypes under end-of-season drought conditions. *Annals of Applied Biology* 122, 357–367.

Nageswara Rao, R.C., Talwar, H.S. and Wright, G.C. (2001) Rapid assessment of specific leaf area and leaf nitrogen (*Arachis hypogaea* L.) using a chlorophyll meter. *Journal of Agronomy and Crop Science* 186, 175–182.

Nam, N.H., Chauhan, Y.S. and Johansen, C. (1993) Comparison of extra-short duration pigeonpea with short-season legumes under rainfed condition on Alfisol. *Experimental Agriculture* 29(3), 307–316.

Nam, N.H., Chauhan, Y.S. and Johansen, C. (2001) Effects of timing of drought stress on growth and grain yield of extra-short duration pigeonpea. *Journal of Agricultural Science, Cambridge* 136, 179–189.

Nelson, D.E., Repetti, P.P., Adams, T.R., Creelman, R.A., Wu, J., Warner, D.C., Anstrom, D.C., Bensen, R.J., Castiglioni, P.P., Donnarummo, M.G., Hinchey, B.S., Kumimoto, R.W., Maszle, D.R., Canales, R.D., Krolikowski, K.A., Dotson, S.B., Gutterson, N., Ratcliffe, O.J. and Heard, J.E. (2007) Plant nuclear factor Y(NF-Y) B subunits confer drought tolerance and lead to improved corn yields on water-limited areas. *Proceedings of the National Academy of Sciences, USA* 104, 16450–16455.

Nigam, S.N., Nageswara Rao, R.C. and Wright, G.C. (2002) Field screening for drought resistance in groundnut. In: Saxena, N.P. and O'Toole, J.C. (eds) *Field Screening for Drought Tolerance in Crop Plants with Emphasis on Rice*. Proceedings of International Workshop on Field Screening for Drought Tolerance in Rice. ICRISAT, India and Rockefeller Foundation, New York, pp. 147–151.

Ortiz, R., Ekanayake, I.J., Mahalakshmi, V., Kamara, A., Menkir, A., Nigam, S.N., Singh, B.B. and Saxena, N.P. (2002) In: Yazima, M., Okada, K. and Matsumoto, L. (eds) *Water for Sustainable Agriculture in Developing Regions – More Crop for Every Scarce Drop*. Proceedings of 8th JIRCAS International Symposium, Tsukuba, Japan. Series No. 10, pp. 11–21.

Osmanzai, M. (1994) Relative performance of sorghum hybrids and open pollinated cultivars under two soil moisture regimes. *International Sorghum and Millets Newsletter* 35, 131.

Pallas, J.R. Jr, Stansell, J.R. and Koske, T.J. (1979) Effects of drought on Florunner groundnuts. *Agronomy Journal* 71, 853–858.

Passioura, J.B. (1977) Grain yield, harvest index and water use of wheat. *Journal of Australian Institute of Agricultural Science* 43, 117–120.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S. and Cassman, K.G. (2004) Rice yields decline with higher night temperature from global warming. *Proceedings of the National Academy of Sciences, USA* 101, 9971–9975.

Prabowo, A., Prastowo, B. and Wright, G.C. (1990). Growth, yield and soil water extraction of irrigated and dryland groundnuts in South Sulawesi, Indonesia. *Irrigation Science* 11, 63–68.

Qin, F., Kakimoto, M., Sakuma, Y., Maruyama, K., Osakabe, Y., PhanTran, L.S., Shinozaki, K. and Yamaguchi-Shinozaki, K. (2007) Regulation and functional analysis of *ZmDREB2A* in response to drought and heat stresses in *Zea mays* L. *Plant Journal* 50, 54–69.

Quan, R., Shang, M., Zhang, H., Zhao, Y. and Zhang, J. (2004) Engineering of enhanced glycine betaine synthesis improves drought tolerance in maize. *Plant Biotechnology Journal* 2, 477–486.

Rachaputi, N.C. and Wright, G.C. (2003) The physiological basis for selection of groundnut genotypes as parents in breeding for improved drought resistance. In: Cruickshank, A.W., Rachaputi, N.C., Wright, G.C. and Nigam, S.N. (eds) *Breeding of Drought-resistant Peanuts*. Proceedings of Collaborative Review Meeting, Hyderabad, India. ACIAR Proceedings No. 112. ACIAR, Canberra, Australia, pp. 10–14.

Rana, B.S., Swarnalata, K. and Rao, M.H. (1997) Impact of Genetic Improvement on Sorghum Productivity in India. *Proceedings of International Conference on Genetic Improvement of Sorghum and Pearl Millet*. INTSORMIL, Lubbock, Texas, USA; and ICRISAT, India, pp. 142–165.

Reddy, B.V.S. (1986) Genetic improvement for drought resistance in sorghum: a plant breeder's view point. In: *Genetic Improvement of Drought Resistance*. Proceedings of Discussion Series of the Drought Research Seminar Forums, pp. 28–32.

Reddy, L.J., Nigam, S.N. and Nageswara Rao, R.C. (1994) Progress in breeding for drought tolerant groundnut varieties at ICRISAT Center. In: Prasad, M.V.R., Kalpana Sastry, R., Raghavaiah, C.V. and Damodaram, T. (eds) *Sustainability in Oilseeds*. Indian Society of Oilseeds Research, Hyderabad, India, pp. 131–133.

Reddy, L.J., Saxena, K.B., Sharma, D., Green, J.M., Rao, A.N. and Kumar, R.V. (1995) Registration of ICPM 93006, ICPM 93007, and ICPM 93009, three short-duration genetic male-sterile parental lines of pigeonpea. *Crop Science* 35, 1715.

Ribaut, J.M. and Ragot, M. (2007) Marker-assisted selection to improve drought adaptation in maize: the backcross approach, perspectives, limitations, and alternatives. *Journal of Experimental Botany* 58, 351–360.

Robertson, M.J., Carberry, P.S., Chauhan, Y.S., Ranganathan, R. and Leary, G.J.O. (2001) Predicting growth and development of pigeonpea: a simulation model. *Field Crops Research* 71, 195–210.

Rosenow, D.T., Quisenberry, J.E., Wendt, C.W. and Clark, L.E. (1983) Drought tolerant sorghum and cotton germplasm. In: Stone, J.F. and Willis, W.O. (eds) *Plant Production and Management under Drought Conditions*. Elsevier Science Publishers, Amsterdam, the Netherlands, pp. 207–222.

Rosielle, A.A. and Hamblin, J. (1981) Theoretical aspects of selection for yield in stress and not-stress environments. *Crop Science* 21, 943–946.

Rucker, K.S., Kvien, C.K., Holbrook, C.C. and Hook, J.E. (1995) Identification of groundnut genotypes with improved drought avoidance traits. *Peanut Science* 22, 14–18.

Saeed, M. and Francis, C.A. (1983) Yield stability in relation to maturity in grain sorghum. *Crop Science* 23, 683.

Saeed, M., Francis, C.A. and Rajewski, J.F. (1984) Maturity effects on genotype × environment interaction in grain sorghum. *Agronomy Journal* 76, 55.

Sari-Gorla, M., Krajewski, P., di Fonzo, N., Villa, M. and Frova, C. (1999) Genetic analysis of drought tolerance in maize by molecular markers. II. Plant height and flowering. *Theoretical and Applied Genetics* 99, 289–295.

Saxena, K.B. (2002) Prospects for hybrid pigeonpea. In: Subramanian, M. (ed.) *Pulses and Oilseeds Production for Sustainable Agriculture*. Tamil Nadu Agricultural University, Coimbatore, India, pp. 28–41.

Saxena, K.B., Chauhan, Y.S., Johansen, C. and Singh, L. (1992) Recent developments in hybrid pigeonpea research. In: *Proceedings of National Symposium on New Frontiers in Pulses Research*. Directorate of Pulse Research, Kanpur, India, pp. 58–69.

Saxena, K.B., Chauhan, Y.S., Singh, L., Kumar, R.V. and Johanson, C. (1996) Research and development of hybrid pigeonpea. Research Bulletin No. 19. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Saxena, N.P. (1987) Screening for adaptation to drought: case studies with chickpea and pigeonpea. In: Saxena, N.P. and Johansen, C. (eds) *Adaptation of Chickpea and Pigeonpea to Abiotic Stresses*. Proceedings of Consultants' Workshop. ICRISAT, Patancheru, India, pp. 63–76.

Saxena, N.P. (2003) Management of drought in chickpea – a holistic approach. In: Saxena, N.P. (ed.) *Management of Agricultural Drought – Agronomic and Genetic Options*. Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi, India, pp.103–122.

Saxena, M.C. and Yadav, D.S. (1975) Some agronomic considerations of pigeonpeas and chickpeas. *International Workshop on Grain Legumes*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 31–61.

Saxena, N.P., Krishnamurthy, L. and Johansen, C. (1993) Registration of a drought resistant germplasm. *Crop Science* 33, 1424.

Schussler, J.R. and Westgate, M.E. (1995) Assimilate flux determines kernel set at low water potential in maize. *Crop Science* 35, 1074–1080.

Sedgley, R.H., Siddique, K.H.M. and Walton, G.H. (1990) Chickpea ideotypes for Mediterranean environments. In: *Chickpea in the Nineties*. Proceedings of Second International Workshop on Chickpea Improvement. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 87–91.

Seetharama, N., Reddy, B.V.S., Peacock, J.M. and Bidinger, F.R. (1982) Sorghum improvement for drought resistance in crops with emphasis on rice. International Rice Research Institute (IRRI), Los Banos, Laguna, Manila, Philippines, pp. 317–338.

Serraj, R., Purcell, L.C. and Sinclair, T.R. (1999) Inhibition of N_2 fixation by drought. A review. *Journal of Experimental Botany* 50, 143–155.

Shaw, R.H. (1976) Water use and requirements of maize – a review. In: *Agrometeorology of the Maize (Corn) Crop*. World Meteorological Organization No. 481, 119–134.

Sinclair, T.R., Tanner, C.B. and Bennett, J.M. (1984) Water-use efficiency in crop production. *BioScience* 34, 36–40.

Singh, L., Gupta, S.C. and Faris, D.G. (1990) Pigeonpea breeding. In: Nene, Y.L., Hall, S.D. and Sheila, V.K. (eds), *The Pigeonpea*. CAB International, Wallingford, Oxon, UK. pp. 375–399.

Srinivasan, G., Zaidi, P.H., Singh, N.N. and Sanchez, C. (2003) Increasing productivity through genetic improvement for tolerance to drought and excess-moisture stress in maize (*Zea mays* L.). In: Veng, S., Craswell, E., Fukai, S. and Fisher, K (eds) *Water in Agriculture for 21st Century*. ACIAR Proceedings No. 116. ACIAR, Canberra, Australia, pp. 227–239.

Stansell, J.R. and Pallas, J.E. Jr (1985) Yield and quality response of Florunner groundnut to applied drought at several growth stages. *Peanut Science* 12, 64–70.

Subbarao, G.V., Johansen, C., Slinkard, A.E., Rao, R.C.N., Saxena, N.P. and Chauhan, Y.S. (1995) Strategies for improving drought resistance in grain legumes. *Critical Reviews Plant Sciences* 14, 469–523.

Tuberosa, R., Salvi, S., Maria, C.S., Pierangelo, L.M.M. and Conti, S. (2002) Mapping QTLs regulating morpho-physiological traits and yield: case studies, shortcomings, and pespectives in drought-stressed maize. *Annals of Botany* 89, 941–963.

Tuberosa, R., Salvi, S., Sanguineti, M.C., Maccaferri, M., Giuliani, S. and Landi, P. (2003) Searching for quantitative trait loci controlling root traits in maize: a critical appraisal. *Plant Soil* 255, 35–54.

Vadez, V., Rao, S., Sharma, K.K., Bhatnagar-Mathur, P. and Devi, J.M. (2007) *DREB1A* allows for more water uptake in groundnut by a large modification in the root/shoot ratio under water deficit. *Journal of SAT Agricultural Research* 5(1). http://www.icrisat.org/journal/volumes5/groundnut/gn3.pdf

van der Maesen, L.J.G. (1986) *Cajanus DC and Atylosia W&A* (*Leguminosae*). *Agricultural University Wageningen Papers 85–4 (1985).* Agricultural University, Wageningen, the Netherlands.

van Oosterom, E.J., Jayachandran, R. and Bidinger, F.R. (1996) Diallel analysis of the stay-green trait and its components in sorghum. *Crop Science* 36, 549–555.

Vasudeva Rao, M.J., Nigam, S.N. and Huda, A.K.S. (1992) The thermal time concept as a selection criterion for earliness in groundnut. *Peanut Science* 19, 7–10.

Virmani, S.M. and Singh, P. (1986) Agroclimatology characteristics of the groundnut regions in the semi-arid tropics. In: *Agrometeorology of Groundnut*. Proceedings of International Symposium. ICRISAT Sahelian Centre, Naimey, Niger and International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 35–46.

Virmani, S.M., Sivakumar, M.V.K. and Sarkar, R.P. (1982) Rainfall probability and tailoring agriculture to match it. In: *Symposium on Rainwater and Dryland Agriculture*. Indian National Science Academy, New Delhi, India, pp. 27–33.

Wallis, E.S., Byth, D.E., Whiteman, P.C. and Saxena, K.B. (1983) Adaptation of pigeonpea (*Cajanus cajan*) to mechanised culture. *Proceedings of Australian Plant Breeding Conference*. Australian Plant Breeding Society, Adelaide, Australia, pp. 142–145.

Welcker, C., Boussuge, B., Bencivenni, C., Ribaut, J.M. and Tardieu, F. (2007) Are source and sink strengths genetically linked in maize plants subjected to water deficit? A QTL study of the responses of leaf growth and of anthesis-silking interval to water deficit. *Journal of Experimental Botany* 58, 339–349.

Westgate, M.E. and Bassetti, P. (1990) Heat and drought stress in corn: what really happens to the corn plant at pollination? In: Wilkinson, D. (ed.) *Proceedings of the 45th Annual Corn and Sorghum Research Conference*. ASTA, Washington, USA. pp. 12–28.

Winkel, T. and Do, F. (1992) Caracteres morphologiques et physiologiques de resistance du mil (*Pennisetum glaucum* (L.) R. Br.) a la secheresse. *L' Agronomie Tropicale* 46, 339–350.

Wright, G.C. and Nageswara Rao, R.C. (1994) Groundnut water relations. In: Smartt, J.E. (ed.) *The Groundnut Crop: a Scientific Basis for Improvement*. Chapman & Hall, London, UK, pp. 281–336.

Wright, G.C., Hubick, K.T. and Farquhar, G.D. (1988) Discrimination in carbon isotopes of leaves correlates with water-use efficiency of field grown groundnut cultivars. *Australian Journal of Plant Physiology* 15, 815–825.

Wright, G.C., Hubick, K.T. and Farquhar, G.D. (1991) Physiological analysis of groundnut cultivar response to timing and duration of drought stress. *Australian Journal of Agricultural Research* 42, 453–470.

Wright, G.C., Nageswara Rao, R.C. and Farquhar, G.D. (1994) Water use efficiency and carbon isotope discrimination in groundnut under water deficit conditions. *Crop Science* 34, 92–97.

Xu, W.W., Subudhi, P.K., Crasta, O.R., Rosenow, D.T., Mullet, J.E. and Nguyen, H.T. (2000) Molecular mapping of QTLs conferring stay-green in grain sorghum (*Sorghum bicolor* L. Moench). *Genome* 43, 461–469.

Yadav, O.P. and Welzien, R.E. (1999) Breeding for adaptation to abiotic stresses. In: Khairawal, I.S., Rai, K.N., Andrews, D.J. and Harinarayana, G. (eds) *Pearl Millet Breeding*. Oxford and IBH Publishers, New Delhi, India, pp. 317–336.

Yadav, R.S., Hash, C.T., Bidinger, F.R., Cavan, G.P. and Howarth, C.J. (2002) Quantitative trait loci associated with traits determining grain and stover yield in pearl millet under terminal drought stress conditions. *Theoretical and Applied Genetics* 104, 67–83.

Yadav, R.S., Bidinger, F.R., Hash, C.T., Yadav, Y.P., Yadav, O.P., Bhatnagar, S.K. and Howarth, C.J. (2003) Mapping and characterization of QTL × E interactions for traits determining grain and stover yield in pearl millet. *Theoretical and Applied Genetics* 106, 512–520.

Yadav, R.S., Hash, C.T., Bidinger, F.R., Devos, K.M. and Howarth, C.J. (2004) Genomic regions associated with grain yield and aspects of post-flowering drought tolerance in pearl millet across stress environments and tester background. *Euphytica* 136, 265–277.

Yau, S.K. (1997) Efficiency of alpha-lattice designs in international variety yield trials of barley and wheat. *Journal of Agricultural Science* 129, 5–9.

Zaidi, P.H., Rafique, S. and Singh, N.N. (2003a) Response of maize (*Zea mays* L.) genotypes to excess soil moisture stress: morpho-physiological effects and basis of tolerance. *European Journal of Agronomy* 19, 383–399.

Zaidi, P.H., Srinivasan, G. and Sanchez, C. (2003b) Morpho-physiological traits associated with variable field performance of different types of maize germplasm across multiple environments. *Maydica* 48, 207–220.

Zaidi, P.H., Srinivasan, G., Cordova, H.S. and Sanchez, C. (2004) Gains from improvement for mid-season drought tolerance in tropical maize (*Zea mays* L.). *Field Crops Research* 89, 135–152.

9 Water Harvesting for Improved Rainfed Agriculture in the Dry Environments

T. Oweis* and A. Hachum

Integrated Water and Land Management Program, International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria;
*email: *t.oweis@cgiar.org*

Background and Definitions

In the arid and semi-arid regions, precipitation is generally lower than potential evaporation, non-uniform in distribution, resulting in frequent drought periods during the crop growing season, and usually comes in intense bursts, resulting in surface run-off and uncontrolled rill and gully erosion.

In the cool winter areas, as in the Mediterranean type of climate, precipitation is less than 300 mm, part of which is lost to evaporation and run-off. The amount stored in the root zone is well below crop water requirements. In dry (semi-arid) tropical areas, such as the Sahel zone in Africa, although mean precipitation is relatively higher (500 mm), a larger portion of precipitation is lost to evaporation.

Where does rainwater in the dry environments go?

A large part of the rainfall returns to the atmosphere directly by evaporation from the soil surface and also a part of that infiltrated into the soil to a small depth evaporates into the atmosphere with no benefits. The part that flows as run-off, if not intercepted, goes to slumps, losing its good quality and evaporating; it may even flow into the sea. It was estimated that only about 10% of the annual rainfall on the dry rangelands of West Asia and North Africa (WANA) is beneficially used for supporting vegetation cover, replenishing the groundwater and other purposes (Oweis and Taimeh, 2001).

Other factors, such as degraded soils, steep topography, poor vegetative cover and unfavourable climate, besides the poor rain characteristics, aggravate the problem, causing irreversible desertification and detrimental loss of both water and land productivity. Water harvesting (WH) is one option that increases the amount of water per unit cropping area, reduces drought and enables use of run-off beneficially (Oweis *et al.*, 1999).

Concept and definition

The principle of agricultural rainwater harvesting is based on the concept of depriving part of the land of its share of precipitation, which is usually small and non-productive, and giving it to another part to increase the amount of water available to the latter part, which originally was not sufficient, and to bring this amount closer to the crop water requirements so that an economical agricultural production can be achieved. Such concentration of precipitation in a smaller area is called water harvesting (WH) and may be defined in various ways such as:

- The process of collecting natural precipitation from prepared watersheds for beneficial use.
- Collecting and concentrating various forms of run-off from precipitation and for various purposes.
- The process of concentrating precipitation through run-off and storing it for beneficial use.

Critchley and Siegert (1991) simply define WH as 'collection of run-off for its productive use'. For Reij *et al.* (1988), it is a hydro-agronomic term covering a whole range of methods of collecting and concentrating various forms of run-off. The concept of WH, as described above, is different from the traditional soil-water conservation practices in which no part of the land is purposely deprived of its share of water. Soil-water conservation practices aim at preventing surface run-off and keeping rainwater in place, whereas WH makes use of, and even induces, surface run-off.

In the WH process the run-off-producing area is adjacent to the cropped area, and part of the land and most of the precipitation water will become productive. More importantly, agricultural production becomes possible, and the WH systems might be for a single purpose or for multi-purpose and built to serve domestic, agricultural, animal or environmental uses.

Water harvesting in the past and the present

Ancient and indigenous WH systems exist in many parts of the world and from many eras, such as contour terracing in the central highlands of Mexico (UNEP, 1983); floodwater farming in desert areas of Arizona and northern Mexico, dating back at least 1000 years (Zaunderer and Hutchinson, 1988 in Critchley and Siegert, 1991); and *khadin* systems in Rajasthan, India, initiated probably in the 15th century (Kolarkar *et al.*, 1983). Reij *et al.* (1988) give a brief review of systems found in sub-Saharan Africa, including rock bunds and stone terraces in what is now Burkina Faso and basin systems in Mali; and Critchley and Siegert (1991) describe the 'caag' system in the Hiraan region of central Somalia.

However, the greatest wealth of ancient WH systems is probably in the Middle East. Reviewing archaeological evidence, Prinz (1996) notes indications of WH structures in Jordan, believed to have been constructed over 9000 years ago, and in southern Mesopotamia, from 4500 BC (Bruins *et al.*, 1986). He continues: 'internationally, the most widely known run-off-irrigation systems have been found in the semi-arid to arid Negev desert region' (Evenari *et al.*, 1971). Run-off agriculture in this region can be traced as far back as the 10th century BC, when it was introduced by the inhabitants of that period (Prinz, 1996). The Negev's most productive period, however, began with the arrival of the Nabateans late in the 3rd century BC.

Nabatean systems have also been discovered in north-western Saudi Arabia, and floodwater diversion systems, believed to be nearly 3000 years old, are still in operation today in Yemen (Brunner and Haefner, 1986) and the South Tihama area of Saudi Arabia. There is also a tradition of WH in northern coastal areas of Egypt, including *wadi* terracing and the utilization of small basins that provide natural run-on for barley cultivation (El-Naggar *et al.*, 1988). Archaeological excavations in Libya have revealed 'structures in an area several hundred kilometers from the coast, where the mean annual precipitation is well below 50 mm. The farming system here lasted well over 400 years and sustained a large stationary population' by producing barley, wheat, olives, grapes, figs, sheep and cattle (Prinz, 1996).

There is also a long history of WH in the Maghreb. In Morocco, Kutsch (1983) described highly developed 'water-concentrating' systems employed by mountain communities in the Anti-Atlas south-west of Agadir, which appear to be of ancient origin: water from mountain slopes is led by stone channels to terraces and to natural basins to support crop and tree growth in areas with a mean annual rainfall of 100–200 mm. Many different traditional systems have been recorded in Tunisia.

A large proportion of WH systems have fallen into disuse, and many that remain appear to be threatened. A sequence of reviews and manuals produced over the last 30 years provide a good inventory of WH techniques, old and new, and also essential information for their implementation (Boers and Ben-Asher, 1982; Frasier and Myer, 1983; Pacey and Cullis 1986;

Reij *et al.*, 1988; Critchley and Siegert, 1991; Tauer and Humborg, 1992; FAO, 1994, 2001; Prinz, 1996; Oweis *et al.*, 1999, 2001, 2004 and Falkenmark *et al.*, 2001). From these and other sources, one may note situations where farmers' innovations, ancient and modern, have stimulated research, and others where research has been started to solve perceived problems at the farm level. A selected sample of national experiences is summarized here to illustrate the range of experiences and potentialities.

Microcatchment WH received most research attention to obtain run-off even from light showers with minimum conveyance losses even on flat surfaces. Catchments tested have most frequently been squares of 100–250 m, feeding a basin in one corner containing a single tree (almond or pistachio). The challenge, the subject of some fairly sophisticated modelling, has been to identify the ratio between catchment and basin surface areas that gives the best compromise between evaporative losses from the basin surface and deep percolation losses below the root zone, particularly in wet years (Boers *et al.*, 1986a,b). Conclusions from such work imply that microcatchment WH is not economically viable in very dry conditions, with mean annual rainfall less than 100 mm. The problem (for economic viability) is to support a reasonably high per-hectare density of trees.

Run-off farming systems have been described by Evenari *et al.* (1968). Tadmor *et al.* (1970) report promising results from water spreading on ecotypes of 30 range species. Water harvesting in Tunisia may be divided broadly into two types: the description and rehabilitation of indigenous systems, and the large-scale technical development programme of the indigenous systems (Ennabli, 1993; Ben Mechlia and Ouessar, 2004). The *meskat* system, which utilizes *tabias* to support olive plantations, is said to cover 300,000 ha in central Tunisia (Prinz, 1996). Essentially it comprises catchments of about 500 m^2 surrounded by *tabia* and spillways to control run-off flow into bunded plots of trees. Undoubtedly, this is a successful system, still well maintained, but Reij *et al.* (1988) comment that it suffers heavily from increasing land pressure, resulting in a decrease in the catchment areas, leading to lower efficiency. The *jessour* system is based upon the cultivation of sediments built up behind large *tabia* (often stone-reinforced and with stone spillways) constructed in a cascade down narrow mountain valleys in southern Tunisia. Akrimi *et al.* (1993), from the Institut des Regions Arides (IRA) near Medinine, reported a multidisciplinary study (technical and socio-economic) involving *jessour* cultivators in the Matmata mountains.

The performance of a small run-off-basin WH system (*negarim*) varied from over 85% to as low as 7%, depending on the size of the catchment and the root-zone storage capacity, as well as rainfall-run-off characteristics affecting deep percolation losses under a typical Mediterranean arid environment in Jordan (Oweis and Taimeh, 1996). In Yemen, focus is on the conservation of the ancient terrace system, which not only conserves soil and water but also controls water from the highest, often degraded, pasture lands down to the protection of the intensively utilized banks of the main *wadis* and the flood irrigation (spate irrigation) systems downstream.

In rainfed coastal areas of Egypt, the main aim was to facilitate the sedentarization of the *bedouin* population, and projects were taken up to rehabilitate degraded rangeland and increase run-off utilization through *wadi* terracing (similar to Tunisian *jessours*) and the enhancement of indigenous run-off farming systems (Perrier, 1988). In Pakistan, work includes WH through site-specific, land-forming techniques; storage in low-cost earthen reservoirs; and utilization as supplemental irrigation. Other work, in highland Balochistan, focuses on ways to improve the indigenous 'khuskaba' and 'sylaba' systems, where bunds are used to guide run-off water and promote infiltration (Rees *et al.*, 1991).

Components and applicability of the system

All WH systems must have the following components:

1. *Catchment area/run-off area*, varying from a few square metres (microcatchment) to as large as several square kilometres (macrocatchment): the part of the land where a portion or all of the precipitation which falls on it runs off its boundaries. It can be agricultural, rocky or marginal land, or even a rooftop or a paved road.

2. *Storage facility*: the place where the run-off water is held from the time it occurs until it is utilized by crops, animals, human beings and/or other uses. Storage can be: (i) above the soil surface as in surface reservoirs or ponds; (ii) in the soil profile as soil moisture; and/or (iii) underground in cisterns or as groundwater in aquifers.
3. *Target or use*: the beneficiary of the stored water. In agricultural production, the target is the plant or the animal, whereas in domestic use, it refers to human beings and their needs.

According to Perrier (1988), a large-scale WH system has four common elements in sequence: catchment, conveyance device, storage facility, and cultivated field. Run-off irrigation, spate irrigation, and run-off farming are among the different forms and practices that come under the umbrella of WH.

The implementation of WH might, however, bring about a number of drawbacks such as: (i) increased soil erosion when slopes are cleared for higher run-off rates; (ii) loss of habitat of flora and fauna on those slopes; (iii) loss of habitat of flora and fauna in depressions; (iv) upstream– downstream conflicts; and (v) competition among farmers and herders.

Water harvesting is low-external-input technology, particularly advantageous in the following situations:

1. In arid and semi-arid areas where rainfall is low and unfavourably distributed, WH makes farming possible on part of the land, provided other production factors such as climate, soils and crops are favourable. Much of the economy of arid lands depends upon livestock, so it is not surprising that most of the work that has been accomplished in WH has been aimed at providing water for livestock. This is generally WH not requiring any pumping or input of energy for water conveyance and/or application.
2. In rainfed areas, WH systems can provide additional water to supplement rainfall to increase and stabilize production. Furthermore, it can alleviate the risk associated with the unpredictability of rainfall in these areas. For this case, the WH system is usually equipped with a facility (above- or underground type) to store the harvested water for later use in supplemental irrigation during drought periods (for details on supplemental irrigation see Chapter 10, this volume).
3. In areas where public water supply for domestic and animal production is not available, inducing run-off from a treated area and storing it in a cistern or other type of reservoir for later use is a common practice in remote areas where no other water resources are available.
4. In arid lands suffering from desertification WH would improve the vegetative cover and can help to halt environmental degradation. Water harvesting has been found to be effective in recharging groundwater aquifers (Nasri, 2002).

Realization of the aforementioned benefits leads to many non-tangible and indirect socio-economical benefits, such as stabilization of rural communities, reducing migration of rural inhabitants to cities, utilizing and improving local skills, and improvement of the standard of living of the millions of poor people living in the drought-stricken areas.

Methods and Relevant Conditions

Classification of water-harvesting systems

There are a dozen different classifications of WH techniques, and the terminology of WH used at the regional and international levels has not yet been standardized. The geometric configuration of WH systems depends upon the topography, the type of catchment treatment, the intended use and personal preference.

Water-harvesting techniques may be grouped into two categories (Table 9.1). First, techniques that directly supply run-off water from a small catchment to the crop, and thus water accumulates around the plant, infiltrates into the soil and is stored in the crop root zone. These are called microcatchment techniques, because the run-off-yielding catchments are usually small and directly adjacent to the targeted crop. The other category is macrocatchment techniques, which concentrate rainwater run-off flowing in an ephemeral *wadi* (natural channel) and store it in a prepared storage facility (such as a reservoir) for subsequent beneficial use. This category also includes macrocatchment techniques in which water is diverted (by proper damming or cross-structure) out of the *wadi* course to inundate nearby lands.

Table 9.1. Guidelines for selecting major water harvesting systems in the drier environments (after Oweis *et al*., 2001).

		Soil		Land		Socio-economics			
Technique	Crop	Depth[a]	Texture	Slope[b]	Stoniness[c]	Capital[d]	Labour[e]	Skill	Storage type
Microcatchment									
Contour ridges	Range	Variable	Variable	Medium, steep	Low, medium	Low	Medium	Local/training	Soil profile
	Field	Medium, deep	Variable	Medium	Low	Low	Medium	Local/training	Soil profile
	Trees	Deep	Medium, heavy	Low, medium	Low	Low	Medium	Local/training	Soil profile
	Vegetable	Medium, deep	Medium, heavy	Low, medium	Low	Low	Medium	Local/training	Soil profile
Semicircular bunds (trapezoidal and triangular)	Range	Medium, deep	Variable	Low, medium	Low, medium	Low	High	Local/no training	Soil profile
	Field	Medium, deep	Medium, heavy	Low, medium	Low, medium	Low	High	Local/no training	Soil profile
	Trees	Deep	Medium, heavy	Low, medium	Low	Low	High	Local/no training	Soil profile
	Vegetable	Deep	Medium, heavy	Low, medium	Low	Low	High	Local/no training	Soil profile
Small pits	Field	Deep	Medium, heavy	Low, medium	Low	Low	Medium	Local/no training	Soil profile
	Range	Shallow, medium	Medium, heavy	Low, medium	Low, medium	Low	Medium	Local/no training	Soil profile
Small basins (*Negarim*)	Range	Medium, deep	Medium, heavy	Low, medium	Low, medium	Low	High	Local/no training	Soil profile
	Trees	Deep	Medium, heavy	Low	Low, medium	Low	High	Local/no training	Soil profile
Run-off strips	Range	Variable	Medium, heavy	Low, medium	Low, medium	Low	Low	Local/no training	Soil profile
	Field	Medium, deep	Medium, heavy	Low, medium	Low, medium	Low	Low	Local/no training	Soil profile
Meskat (*Khushkaba*)	Trees	Deep	Medium, heavy	Low, medium	Low, medium	Low	Low	Local/no training	Soil profile
	Field	Medium	Medium, heavy	Low, medium	Low, medium	Low	Low	Local, no training	Soil profile
Contour bench terraces	Trees	Deep	Medium, heavy	Steep	Low, medium	High	Medium	External skill	Soil profile
	Field	Medium	Medium, heavy	Steep	Low, medium	High	Medium	External skill	Soil profile
Macrocatchment and floodwater									
Small farm reservoirs	All crops	Variable	Medium, heavy	Low, medium	Variable	High	High	External skill	Surface/ subsurface
Wadi-bed cultivation	Trees/vegetable	Medium, deep	Medium, heavy	Low, medium	Low	Medium	Medium, high	Local	Surface/soil
Jessour	Trees	Medium, deep	Medium, heavy	Medium, steep	Variable	Medium	High	Local/training	Surface/soil
Water spreading	Field/trees	Medium, deep	Medium, heavy	Low, medium	Low, medium	Medium	Medium	External skill	Soil profile
Large bunds	Trees	Deep	Medium, heavy	Low, medium	Low, medium	Medium	Medium	Local/training	Soil profile
	Field	Medium	Medium, heavy	Low, medium	Low	Medium	Medium	Local/training	Soil profile
	Range	Shallow, medium	Variable	Low, medium	Variable	Medium	Medium	Local/training	Soil profile
Tanks and *hafair*	All crops	Variable	Medium, heavy	Low	Variable	Medium, high	Medium	External skill	Surface/ subsurface
Cisterns	Vegetables/ trees	Deep	Rock	All slopes	Variable	Medium	High	Local/training	Subsurface

[a] Shallow <50 cm, medium 50–100 cm, deep >100 cm; [b] low <4%, medium 4–12%, steep >12%; [c] low <10%, medium 10–25%, high >25%; [d] low <$ 25/ha, medium $ 25–100/ha, high >$ 100/ha; [e] low <5 man-day/ha, medium 5–20 man-day/ha, high >20 man-day/ha.

The widely used microcatchment WH techniques are contour ridges, semicircular and trapezoidal bunds, and small run-off basins. The famous *zay* pitting system in sub-Saharan Africa is used mainly for the cultivation of annual crops, especially cereals such as millet, maize and sorghum. A success story for microcatchment WH is reported in Box 9.1.

Macrocatchment systems are characterized by having run-off water collected from relatively large catchments. Often the catchments are natural rangeland or a mountainous area. Catchments for these systems are mostly located outside farm boundaries, where individual farmers have little or no control over them. Harvested run-off may be stored in the soil profile for direct use by the crop, in aquifers as a recharge system or in a storage facility ranging from an on-farm pond or tank to a small dam constructed across the *wadi*, and used later for domestic purpose, livestock and supplemental irrigation. Several issues, both technical and socio-economic, need to be considered for optimal implementation of this WH system. Two success stories for macrocatchment WH are reported in Box 9.2 and Box 9.3.

Constraints to adoption

- The difficulties due to farmers' unfamiliarity with the technology.
- Conflicts and disputes on water rights, land ownership and use.
- Lack of adequate characterization of rainfall, evapotranspiration and soil properties.
- Risk of crop failure in drought years may severely hit the poor.
- Weak institutions and lack of policies that deal with conjugate use of green and blue waters.

Microcatchment systems are usually within an individual farm perimeter. This is a simple and low-cost approach, although farmers may experience some difficulty with elements requiring precision, such as following the contour lines or determining maximum slope. The community may be involved in micro- and macrocatchment WH systems, typically through a careful locally planned programme such as the community watershed programme in India (Joshi *et al.*, 2005; Chapter 1, this volume). Ideally, these should be planned at the watershed level with farmers' participation in their planning. Community-based management, farmer participation in planning and cost sharing, or the

Box 9.1. Small run-off-harvesting basins for fruit trees in Jordan.

The arid land of Jordan is of Mediterranean climate, with a mean annual rainfall of 100–200 mm, which occurs mainly in the cold winter, from December to March. Long, hot and dry summers make rainfed agriculture uneconomic. Farmers in the area depend on livestock using poor natural vegetation and limited groundwater for domestic use. There are no fruit trees without irrigation in this zone. In 1987, a project was launched by the University of Jordan to diversify farmers' production by introducing tree crops using additional water from a microcatchment water-harvesting system. The *negarim* (small diamond basins) system with plots of 50–100 m^2 was constructed on deep soils (see figure below). Almonds and olive trees were planted in the winter season. Polymers were added to the planting pit to increase soil water storage capacity to sustain the long dry summer.

Trees planted survived the drought and grew satisfactorily over the seasons and are still producing after 23 years. Farmers adopted the technology in several areas of the dry zone. Although the intervention was very successful, there were some problems. The selection of deep soils and drought-tolerant species are so critical in this area. The soil should be deep enough to hold sufficient water to sustain the plant for the whole dry season. It is important that the crop is tolerant to drought so that the trees do not die after some years, even if drought occurs.

The *negarim* (small basin) water-harvesting system.

Box 9.2. Cisterns in north-western Egypt.

Cisterns are ancient, indigenous rainwater-harvesting systems, used mainly for supplying human and animal water needs in water-scarce areas. They are usually subsurface reservoirs, with capacity ranging from 10 to 500 m^3. Along the north-west coast of Egypt, with an average annual rainfall of about 150 mm, no other source of freshwater exists. Run-off resulting from a few major rainstorms in winter is directed into cisterns from adjacent catchments or through channels from remote areas. The run-off from the first rainfall event of a season is usually diverted away from the cistern to reduce the likelihood of pollution. Settling basins are also provided at the cistern entrance. A bucket and a rope are typically used to lift water.

Farmers in north-western Egypt dig large cisterns (200–300 m^3) in the earth deposits underneath a layer of solid rock (see figure below). Modern concrete cisterns are now being constructed in places where there is no such rocky layer. Water is used not only for human and animal needs but also for growing cash crops in home gardens.

However, traditional cisterns require a large catchment area, having small capacity, with high construction cost and maintenance. A project to deal with these issues and to provide technical and financial support to the local communities was initiated in 1998. Three interventions were found to substantially improve the system efficiency:

1. Clearing, cleaning and smoothing of the catchment area substantially improved the run-off efficiency and water quality.

2. The cistern's seasonal water capacity was more than tripled through efficient management, without increasing its actual size and cost. Hydrological studies showed that the cistern could be re-filled at least three times during the rainy season. Farmers were encouraged to use the water from the first and second filling directly for agriculture, and to preserve the third filling for human and animal consumption during the summer. The availability of manual pumps and low-cost pipes helped to make the task easier.

3. The water use efficiency was improved by providing a small kit of materials and introducing a few changes in the agricultural production system at the home-garden level. For example, placing high-value crops such as seedlings and vegetables in plastic houses became popular and provided additional income to the farmers, with little additional water.

Cistern in northern Egypt.

establishment of a cooperative can be among alternatives recommended to manage these reservoirs and to overcome the problem of smallholdings (Wani *et al.*, 2008). A successful system, however, must be technically sound, properly designed and maintained, economically feasible, and capable of being integrated into the social traditions and abilities of the users.

Potential in arid and semi-arid regions

Improvement of agricultural productivity in the dry areas goes through the development of land management practices. Water harvesting is thus based on the dryland management principle that aims to deprive part of the land of its low and unproductive share of rain in order to add it to another part of the land and obtain economic yields (Oweis *et al.*, 2001). Successful implementation of WH practices requires significant knowledge input from hydrology, agronomy and sociology. Data on rainfall, soil and relief, as well as information on the cropping systems and the local socio-economic conditions, are all needed. Identification of areas suitable for WH practices is crucial for successful development of WH. Because WH deals with large areas, the cost of surveys and analysis could be prohibitive

Box 9.3. Small farm reservoirs in Jordan.

Farmers in the dry areas store water collected during the rainy winter for later use, either in the same season or in the following dry season. This practice is useful in rainfed areas where rain is not sufficient to support rainfed crops in winter and/or when the water is needed for domestic or livestock use.

Three small earth dams, in a typical area of the Jordan steppe (*Muaqqar*), were built across a *wadi*, creating small farm reservoirs of 10,000–20,000 m^3 (see figure below). The reservoirs' water has been used to irrigate field crops and trees and support livestock for over 20 years. Evaluation of run-off adequacy, proper dam construction, adequacy of spillway, siltation and the consequences downstream are major issues. The experience revealed the following prerequisites for success:

1. Water is required for multiple uses, such as for drinking, livestock or environmental purposes.
2. Adequate and sustainable run-off is available. Potential upstream development may reduce run-off amounts downstream.
3. Farmers' capacity to manage the facility.
4. Water rights and requirements of other uses are considered.

Large numbers of smaller-size reservoirs distributed over the catchment area have real advantages in water savings, social equity and environmental impact. The commonly practised method of delaying the use of water stored from winter to summer may not be the best strategy. To maximize the benefits, it is generally recommended that water be transferred from the reservoir and be stored in the soil as soon as possible. Storing reservoir water in the soil profile for direct use by crops in the winter season saves substantial evaporation losses that normally occur during the high evaporative demand period. Emptying the reservoir early in the winter provides more capacity for other run-off events. Furthermore, higher reservoir water use efficiency can be achieved by supplemental irrigation of winter crops over full irrigation of summer crops.

Small farm reservoir in Jordan steppe.

for carrying out the necessary work. Low-cost methods for assessing the potential of WH are of greatest interest to stakeholders and investment agencies.

Satellite and remote-sensing technologies coupled with geographical information systems (GIS) are the most powerful and reasonably cost-efficient methods/tools that help in assessing the potential of WH. The principal steps used to analyse remotely sensed data to identify suitable areas for WH include: (i) definition of data needs, e.g. land use, geology, pedology, hydrology, etc.; (ii) data collection using remote sensing and other techniques; (iii) data analysis, e.g. measurement, classification and estimation analysis; (iv) verification of the analysis results; and (v) presenting the results in a suitable format, such as maps, computer data file, written reports with diagrams, tables, maps, etc.

In this section summaries of two cases, one in Syria and another in Tunisia, for assessing the potential of WH in WANA are presented.

The case of Syria

The assessment was taken up by matching, in a GIS environment, simple biophysical information, systematically available at country level, to the broad requirements of the specified WH systems (De Pauw *et al*., 2008). The systems evaluated include 13 microcatchment systems, based on combinations of six techniques and three crop groups, and one generalized macrocatchment system. The main microcatchment techniques for which a suitability assessment can be applied at the level of Syria are: contour ridges, semicircular and trapezoidal bunds, small pits, small run-off basins, run-off strips, inter-row systems and contour-bench terraces. Three crop groups (rangeland, field crops and fruit trees) were considered.

The environmental criteria for suitability were based on expert guidelines for selecting WH techniques in the drier environments (Oweis *et al*., 2001). They included precipitation, slope, and soil depth, texture and salinity, as well as land use/land cover and geological substratum. The data set included interpolated surfaces of mean annual precipitation, the SRTM digital elevation model, a soil map of Syria, a land use/land cover map of Syria and a geological map of Syria.

The results of the suitability assessments are presented as a set of 14 maps and summarized at provincial and district level in the form of tables. As a sample output, Figs 9.1 and 9.2 show the suitability of contour ridges for range shrubs and small run-off basins for tree crops, respectively, in Syria (De Pauw *et al*., 2008). Validation by comparing the results predicted by the model with an assessment of actual conditions in sample locations is required.

The case of Tunisia

A work aimed at developing a methodology for the assessment of land suitability for WH systems was carried out under the Comprehensive Assessment initiative. Available data and knowledge were used together with modern tools such as image processing and GIS to map the

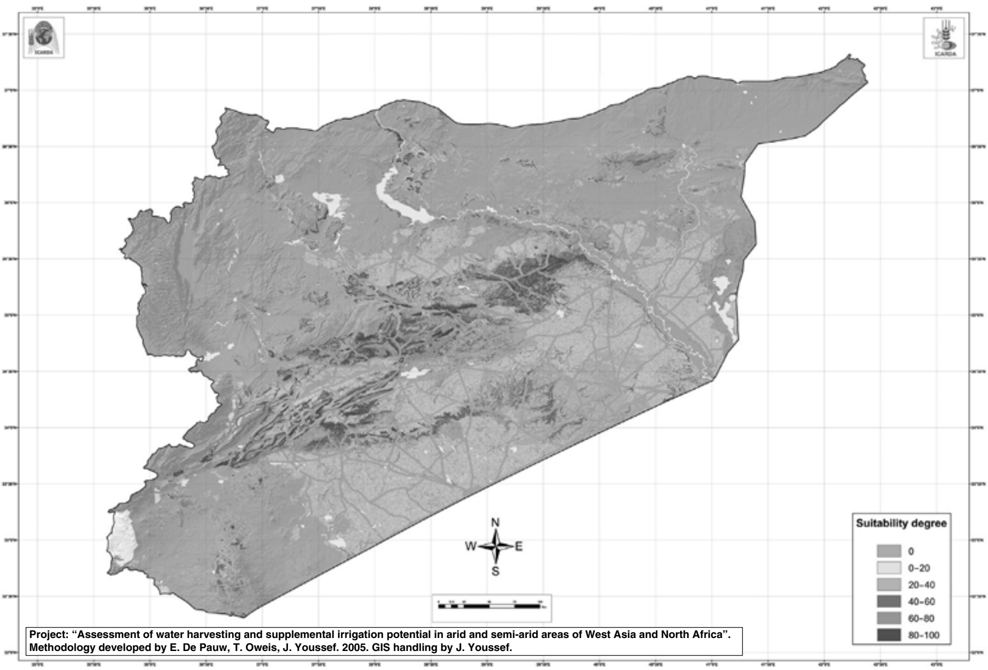
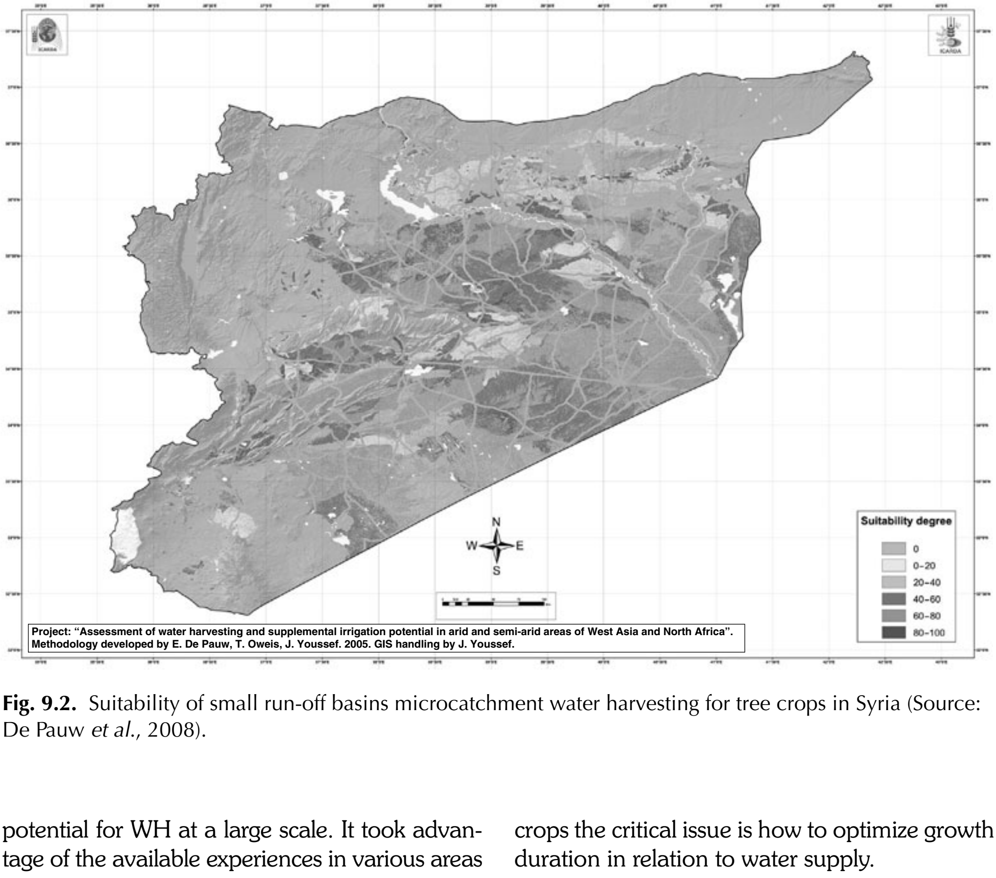


Fig. 9.1. Suitability of contour ridges microcatchment water harvesting for range shrubs in Syria (Source: De Pauw *et al.,* 2008).



Project: "Assessment of water harvesting and supplemental irrigation potential in arid and semi-arid areas of West Asia and North Africa". Methodology developed by E. De Pauw, T. Oweis, J. Youssef. 2005. GIS handling by J. Youssef.

Fig. 9.2. Suitability of small run-off basins microcatchment water harvesting for tree crops in Syria (Source: De Pauw *et al.*, 2008).

potential for WH at a large scale. It took advantage of the available experiences in various areas of the region but particularly in Tunisia.

The work is concentrated in the arid region of southern Tunisia, where annual rainfall is less than 250 mm. Understanding of social factors is a prerequisite to any successful implementation of WH systems; therefore, a spatial integration of socio-economic data has been made in the study. There is a common agreement that whatever the soil and water conservation measures are they must first of all support a positive economic alternative to existing conditions in order to get farmers' acceptance.

The number of practices involving the use of run-off water to supplement rainfall deficiencies is quite large. There are probably more than 25 techniques in Tunisia. They vary according to a multitude of parameters but all attempt to optimize the use of available water, soil and biological resources. To make the best use of run-off water, characteristics such as rooting system, drought and flood resistance are important criteria for fruit trees, but for annual crops the critical issue is how to optimize growth duration in relation to water supply.

Jessour and *tabia* are widely practised in Tunisia and are mainly used for growing trees and annual crops (Fig. 9.3). These WH structures are situated in gullies or in *wadi* tributaries to form deep and adequate soil substratum, collected from erosion of upstream contributing areas. For reasons of practicality, the selected systems were limited to the *jessour* and *tabia* techniques, which are widely used in the mountainous area of southern Tunisia, where annual rainfall is below 250 mm (Ben Mechlia *et al.*, 2006).

In southern Tunisia, *jessour* structures are used with a slope range of 2.7–25% to collect water from a watershed area of 100 ha. In areas with slope of 1–2.7%, larger watersheds (370 ha) are needed in order to generate enough run-off water to support long-term farming with the *tabia* system. Farmers are involved in all subsequent stages of the work, alongside the researchers, identifying, testing and eventually demonstrating successful new techniques.

Fig. 9.3. *Jessours* are widely practised in Tunisia for water harvesting.

Economics of Water Harvesting

Direct versus indirect benefits

Most of the available work on WH deals with technical, agronomical and social aspects of this practice; however, few and inconclusive assessments are available on the economical feasibility of WH in the drier environments. In India, detailed meta-analysis of watershed programmes has documented the benefits of WH, including economic parameters such as benefit–cost ratios and internal rate of returns (for details see Chapter 14, this volume). However, benefits of WH in these environments include, in addition to food and feed production (direct benefits), substantial environmental and social returns, such as combating land degradation and migration from rural to urban areas and employment. Methodologies for evaluating indirect benefits are sometimes controversial and the private sector is often not interested in these benefits. Economic assessment of macrocatchments WH is more complicated because of the upstream–downstream interactions in addition to social and environmental issues.

Microcatchments for field crops

In arid and semi-arid regions, limited water availability and soil fertility, in almost all cases, are the major constraints to dry farming. It is generally recognized that WH can significantly increase crop yields in such areas. The economic feasibility of microcatchment WH depends on the following interrelated issues:

1. Whether or not the cropped area under WH yields more than that of the total area (cropped and catchment) under purely rainfed conditions (i.e. no WH intervention). For example, if the catchment area to the cropped area ratio is 1:1, is the net return of the *cropped area* more than that of the purely rainfed part of the *total area* without WH intervention? This would require that the yield in the cropped area should be at least twice that of purely rainfed area. The assumption here is that the catchment area is cultivable. The rationale behind this question is that there is an opportunity cost for the catchment land, which could be used to grow crops instead of *catching* water. This is particularly true in the case of microcatchment WH under limited suitable arable land.

2. The differences in the fixed and variable costs associated with the proportions of the crop and catchment areas play a role because a smaller cropped area needs less seed and fertilizers (if any) and probably less labour for preparation.
3. Whether there is an increase in the price of outputs relative to the costs of inputs or a decrease in the cost of inputs relative to the price of outputs. This depends on market dynamics.

With these issues in mind, a 6-year economical and viability assessment of WH for wheat and barley in the farmers' fields of highland Balochistan (Pakistan), where total seasonal rainfall ranges between 96 and 282 mm, was conducted and it revealed the following (Rodriguez *et al*., 1996):

1. Water harvesting is a low-cost method of generating run-off and increasing yield, in some cases up to threefold. Wheat is more responsive to water availability than barley. However, if the yield is adjusted to the total area (cropped plus catchment areas), it becomes less than the yield of the control (i.e. the whole area cropped under rainfed conditions) in most cases.
2. The increase in wheat yield (biomass) per unit cropped area is more pronounced in the drier years. For example, the yield is increased by 180% and 80% under seasonal rainfall of 102 mm and 282 mm, respectively.
3. For wheat, the ratio of catchment area to cropped area of 1:1 (i.e. one-half of the area used for water catchment and one-half for planting) had 23% higher net benefits than the control and decreased the variation in income by 19%. Thus, WH has positive effects on both stability and income, which are vital to wheat growers in very marginal areas. For barley, the 1:1 area ratio fields yielded 25% lower net benefits than the control and increased variation in net benefits by 4%.
4. Due to waterlogging, however, for wheat the 2:1 area ratio fields had a 29% lower net benefit than the control, but the variation in net benefits was reduced by 8%. For barley the 2:1 area ratio had 36% lower net benefits than the control and 18% more variation. To overcome this problem, it is suggested that the crops are grown in broad beds, with furrows at 1–2 m intervals, where the run-off water could be collected.

Macrocatchments in sub-Saharan Africa

A second case study for economic assessment of WH is from Africa. Rainwater harvesting (RWH) is being widely promoted as a way to improve the production of crops and livestock in semi-arid areas of eastern and Southern Africa. However, evidence of the performance of RWH with respect to food and income security, and thus reduction of poverty, is limited and far apart. In Tanzania, farmers are using RWH technology to produce maize, paddy and vegetables in semi-arid areas where it would otherwise be impossible or very difficult to produce (Hatibu *et al*., 2006). The economics of these practices are analysed in two contrasting districts over a period of 5 years. Gross margin analyses were used to assess the economic performance of different rainwater-capturing systems with respect to return to labour and thus income generation. It then provides an analysis of the priority actions needed to enhance the performance of RWH in the semi-arid areas of the region. The evaluated WH systems included microcatchment and macrocatchment with floodwater diversion and small storage ponds.

Results show that most farmers have invested heavily in terms of labour to establish and maintain earth structures for the capture of run-off without corresponding investment in nutrient management, leading to low yields for the cereal enterprises. When this is coupled with low farm-gate prices, the improvements of RWH for cereal systems did not lead to a corresponding increase in returns to labour for the majority. However, high returns of US$10–200/person/day were obtained when RWH was applied to vegetable enterprises. Therefore, for RWH to contribute to improved incomes and food security, smallholder farmers should be assisted to change from subsistent to commercial objectives with market-oriented production of high-value crops combined with processing into value-added products. This will require farmers to participate in food markets and thus increasingly depend on the market for food security as opposed to emphasizing self-sufficiency at the household level.

Yuan *et al*. (2003) evaluated the economic feasibility of agriculture with RWH and supplemental irrigation in a semi-arid region. The results show the importance of making full use of every open-air hardened surface to collect rainwater and to establish rainwater catchment areas by utilizing unoccupied land. The results also show that the usefulness of the harvested rainwater is enhanced when water-saving and seepage-prevention techniques are employed. The results indicate that in order to maximize investment it is essential to select crops with a water requirement process that coincides with local rainfall events. Potato was found to be the most suitable crop in the studied region. The economic indices for potato were superior to spring wheat, maize and wheat/maize intercropping. Therefore, potato production using RWH and supplemental irrigation is the best alternative for cropping systems in the semi-arid region of Gansu, China.

Water Harvesting for Supplemental Irrigation

In Kenya (Machakos district) and Burkina Faso (Ouagouya), there is significant scope for improving water productivity in rainfed farming through supplemental irrigation, especially if combined with soil fertility management. Surface run-off from small catchments (1–2 ha) was harvested and stored in manually dug farm ponds (100–250 m^3 storage capacity). Simple gravity-fed furrow irrigation was used. During the three and five experimental rainy seasons in Burkina Faso (mono-modal rain pattern) and Kenya (bi-modal rain pattern), respectively, supplemental irrigation amounted, on average, to 70 mm per growing season with a range of 20–220 mm. Seasonal rainfall ranged from 196 to 557 mm in Kenya and 418 to 667 mm in Burkina Faso. In Kenya, one rainy season was classified as a meteorological drought (short rains of 1998/99), resulting in complete crop failure, while one season at each site (long rains of 2000 in Kenya and the rainy season 2000 in Burkina Faso) resulted in complete crop failure for most neighbouring farmers, but the WH system enabled the harvest of an above-average yield (>1 t/ha). The highest improvement in yield and water use efficiency was achieved by combining supplemental irrigation and fertilizer application (for details on supplemental irrigation see Chapter 10, this volume). Interestingly, in both the locations, fertilizer application alone (in Kenya with low application of 30 kg nitrogen/ha and high application of 80 kg nitrogen/ha) resulted in higher average yield and water use efficiency than WH alone during years with gentle dry spells (for seasons with severe dry spells, e.g. long rains of 2000 in Kenya, non-irrigated crop resulted in complete crop failure). Nevertheless, it indicates that the full benefits of WH for supplemental irrigation can only be met by simultaneously addressing soil fertility management (Rockström *et al.*, 2001).

For resource-poor smallholder farmers in water-scarce areas, even small volumes of stored water for supplemental irrigation can significantly improve the household economy. In Gansu Province in China, small (10–60 m^3; 30 m^3 on average) subsurface storage tanks are promoted on a large scale. These tanks collect surface run-off from small, often treated catchments (e.g. with asphalt or concrete). Research using these subsurface tanks for supplemental irrigation of wheat in several counties in Gansu Province (Li *et al.*, 2000) indicated a 20% increase in water use efficiency (rain amounting to 420 mm + supplemental irrigation ranging from 35 to 105 mm). Water use efficiency increased on average from 8.7 kg/mm/ha for rainfed wheat to 10.3 kg/mm/ha for wheat receiving supplemental irrigation. Incremental water use efficiency ranged from 17 to 30 kg/mm/ha, indicating the large relative added value of supplemental irrigation. Similar results were observed in maize, with yield increases of 20–88%, and incremental water use efficiencies ranging from 15 to 62 kg/mm/ha of supplemental irrigation (Li *et al.*, 2000).

Benefiting from the Chinese experience with subsurface tanks, similar systems are at present being developed and promoted in Kenya and Ethiopia. In Kenya (Machakos district) these tanks are used to irrigate kitchen gardens and enable farmers to diversify sources of income from the land. The micro-irrigation schemes are promoted together with commercially available low-pressure drip-irrigation systems. Cheap drip kits (e.g. the Chapin bucket kit) save water and labour, and are increasingly adopted among farmers, e.g. in Kenya. Combining WH with drip irrigation can result in very significant water-productivity improvements.

Evaporation and seepage losses and silting are major problems of storage reservoirs. It is important to minimize the adverse effects of these problems in the design of a surface-water storage facility. Silting may be minimized by arresting the silt and sand on the catchment area itself, mainly through controlling catchment erosion but also by installing silt-traps. Seepage can be minimized by careful site selection, avoiding sand, gravel and highly permeable soils, or by compaction of the reservoir bottom and sides. Other than minimizing the water surface area, there is no cost-effective way of eliminating evaporation losses from open water bodies. Therefore, to use collected run-off water more efficiently, it is highly recommended to apply this water to the cropped area as soon as it is needed as supplemental irrigation.

Investing in storage facilities, among other opportunities, seems promising in the drier environments. Other opportunities are related to manufacturing and production of low-cost and environment-friendly materials and implements for surface run-off inducement (Box 9.4). This may include material and techniques to reduce evaporation and seepage losses. Opportunities may also include the production of low-cost materials and/or additives, such as polymers, that could be added to and mixed with the soil of the cropped area to increase its water-holding capacity, especially in the case of light and/or shallow soils.

Combating Desertification with Water Harvesting

Rangelands in the dry areas are a very fragile ecosystem. They receive inadequate annual rainfall for economical dry farming. Natural vegetation and plants undergo severe moisture-stress periods, which significantly reduce growth and result in very poor vegetative cover. Part of the rain which flows as run-off usually forms erosive streams and results in severe soil

Box 9.4. Rehabilitation of rangelands in Syria.

The Syrian *Badia* (rangeland) consists of about 55% of the total area of the country, with an average annual rainfall of less than 200 mm. Livestock-based production systems in this area provide about two-thirds of the red meat and one-third of the milk production of the country. Natural vegetation is an important source of feed for the livestock. The *Badia* production system is very fragile and degraded because of high spatial and temporal variation of rainfall, overgrazing and low vegetation regeneration and lack of appropriate rainwater management. Water harvesting is an efficient tool to improve soil-moisture storage and shrub establishment.

In 1995, a project was launched to rehabilitate an area of about 36,000 ha through integrating micro-catchment water-harvesting techniques for sustainable biomass production (Somme *et al.*, 2004). Two run-off water-harvesting sites were developed for evaluation; one site was developed by manual construction of semicircular bunds, while the other with mechanically built contour ridges. A suitable area was kept untreated as a control. *Atriplex halimus* and *Salsola vermiculata* shrubs were planted.

The water-harvesting system managed to mitigate the effect of drought and rainfall variation in the drier environments, as indicated by the significant increase in the shrub survival rates (see table below). The shrub survival rate was increased from about 3% to about 90% by using water harvesting. The limited surviving shrubs on the control died during the first year of drought. Shrubs supported with water-harvesting bunds survived the 3 consecutive drought years and are still growing vigorously. The assessed interventions are simple to construct and maintain even by small-scale farmers.

Shrub survival rate (% by number) for the semicircular bunds of 2, 4 and 6 m diameter in the Syrian *Badia* (rangeland). (Source: Somme *et al.*, 2004).

Year	Rainfall (mm)	No. of bunds	Land slope 2%			No. of bunds	Land slope 5%		
			2 m	4 m	6 m		2 m	4 m	6 m
1997/98	174	23	74	75	70	20	96	98	97
1998/99	36	12	52	54	51	7	92	95	93
1999/00	42	5	28	30	22	2	92	93	89

erosion and land degradation. Increasing consumer demand for sheep, meat and milk, in combination with rapid population growth and inappropriate government policies, have stimulated a substantial increase in the livestock population.

Water harvesting can improve the vegetative cover, increase the carrying grazing capacity of rangeland and help halt environmental degradation (Fig. 9.4). It can be an individual or community response to an environmental limitation. Practices of rainwater harvesting provide a sound basis for improved resources management, reduce cost and provide people with tools for improving the rangelands and, hence, their income and livelihoods (Box 9.4).

Land tenure in rangelands is a major constraint to development and varies from one country to the other. In Syria, for example, rangeland is largely public land, but other forms of land tenure such as rented and private land ownership also exist. In Jordan, however, most of the rangeland is private tribal lands. Owing to lack of appropriate land tenure systems in most of the dry countries, communal land is used as common property, where overgrazing is a common practice and little attention is given to sustainability.

Although rainfall is generally higher in the mountainous areas, they have problems of accessibility and marginalized poor communities. The complex landscape consists of steep slopes, terraced croplands, sloping rangelands and scattered patches of shrubs and trees. Most of the agriculture in the area depends on direct rainfall, and irrigated agriculture takes place along the banks of the *wadis* that dissect the mountains. The main cause of land degradation here is due to water erosion.

The degradation of the indigenous terraces in the Yemeni mountains is well known and documented. Poor maintenance and improper run-off management are believed to be the major sources of soil erosion that occurs as the result of successive failure of these terraces, which require a high annual maintenance cost. Steep topography, coupled with relatively high rainfall, is another factor that, in the absence of appropriate measures for sustainable natural resource management, contributes to soil erosion and other types of land degradation.

Considerable progress has been made in identifying efficient WH and use schemes for both crop production and combating desertification. Constraints to the implementation and adaptation of these schemes include farmers' unfamiliarity with the technology; conflicts and disputes on water rights, land ownership and use; and lack of adequate characterization of rainfall, evapotranspiration and soil properties.

One of the crucial social aspects for the success is the involvement/participation of the stakeholders or beneficiaries. All stakeholders have to get involved in planning, designing and implementation of WH structures. A consensus is necessary for operation and maintenance of these structures. Involvement of local NGOs (non-governmental organizations) may also benefit the community for collective action.

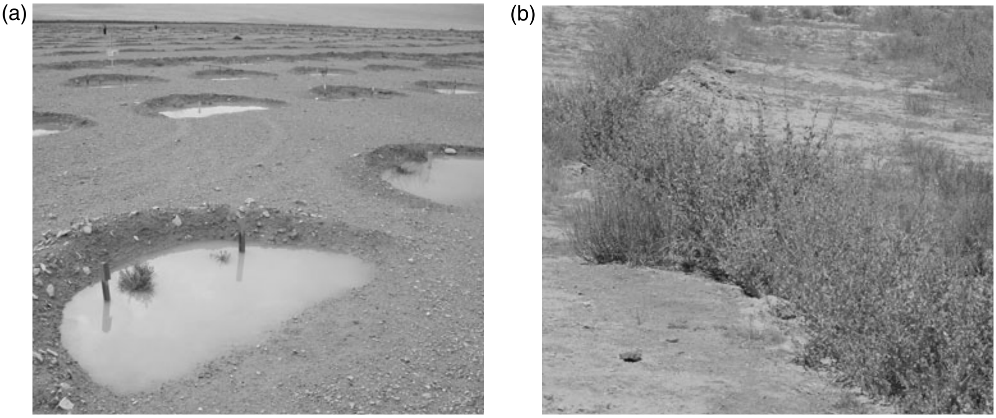


Fig. 9.4. Manually developed semicircular bunds: (a) field plot and shrub after 2 years showing water harvested after a storm; (b) field plot and shrub after 4 years.

Conclusions

Water harvesting is one option that increases the amount of water per unit cropping area, reduces drought impact and enables the use of run-off beneficially. It is low-external-input technology that makes farming possible on part of the land, provided other production factors such as climate, soils and crops are favourable. In arid lands suffering from desertification, WH would improve the vegetative cover and can help to halt environmental degradation. Water harvesting has been found to be effective in recharging groundwater aquifers. Non-tangible and indirect socio-economic benefits, such as combating land degradation, stabilization of rural communities, reducing migration of rural inhabitants to cities, utilizing and improving local skills, and improvement of the standard of living of the millions of poor people living in the dry areas, should be taken into consideration when conducting WH economic and feasibility studies.

Successful implementation of WH practices requires significant knowledge input from hydrology, agronomy and sociology. Identification of areas suitable for WH practices is crucial for successful development of WH. Low-cost methods for assessing the potential of WH are needed and they are of greatest interest to stakeholders and investment agencies. Rainwater harvesting should suit its purpose, be accepted by the local population and be sustainable in the local environment. The decision-making process concerning the best method applicable in particular environmental and geophysical conditions depends on the kind of crop to be grown and prevalent socio-economic and cultural factors. Local availability of labour and materials are the most important factors. The accessibility of the site and distance from the village have also to be considered for construction of WH structures. One of the crucial social aspects for the success is the involvement/participation of the stakeholders or beneficiaries. All stakeholders have to get involved in planning, designing and implementation of WH structures.

The implementation of WH, however, requires taking care of possible drawbacks such as: (i) increased soil erosion and loss of habitat of flora and fauna in macrocatchments; (ii) upstream–downstream conflicts; and (iii) competition among farmers and herders.

References

Akrimi, N., Neffati, M., Taamallah, H. and Sghaier, M. (1993) Resource management in the Graguer basin of southern Tunisia. In: *Proceedings of Workshop on Dryland Resource Management and the Improvement of Rainfed Agriculture in the Drier Areas of West Asia and North Africa.* International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Ben Mechlia, N. and Ouessar, M. (2004) Water harvesting systems in Tunisia. In: Oweis, T., Hachum, A., Bruggeman, A. (eds) *Indigenous Water Harvesting Systems in West Asia and North Africa.* International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria, pp. 19–41.

Ben Mechlia, N., Oweis, T., Masmoudi, M., Khattali, H., Ouessar, M., Sghaier, M., Bruggeman, A. and Anane, M. (2006) Assessment of water harvesting potential in arid areas: methodology and a case study from Tunisia. *The Comprehensive Assessment of Water Management in Agriculture,* Research Report. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Boers, T.M. and Ben-Asher, J. (1982) A review of rainwater harvesting. *Agricultural Water Management* 5, 145–158.

Boers, T.M., De Graaf, M., Feddes, R.A. and Ben-Asher, J. (1986a) A linear regression model combined with a soil water balance model to design micro-catchments for water harvesting in arid zones. *Agricultural Water Management* 11, 187–206.

Boers, T.M., Zondervaan, K. and Ben-Asher, J. (1986b) Micro-catchment-water-harvesting (MCWH) for arid zone development. *Agricultural Water Management* 12, 21–39.

Bruins, H.J., Evenari, M. and Nessler, U. (1986) Rainwater harvesting agriculture for food production in arid zones: the challenge of the African famine. *Applied Geography* 6, 13–33.

Brunner, U. and Haefner, H. (1986) The successful floodwater farming systems of the Sabeans, Yemen Arab Republic. *Applied Geography* 6, 77–89.

Critchley, W. and Siegert, K. (1991) *Water Harvesting: a Manual for the Design and Construction of Water Harvesting Schemes for Plant Production.* AGL Miscellaneous Paper No. 17. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

De Pauw, E., Oweis, T. and Yousef, J. (2008) Integrating expert knowledge in GIS to determine biophysical potential for water harvesting: a case study for Syria. *The Comprehensive Assessment of Water Management in Agriculture*, Research Report. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

El-Naggar, S., Perrier, E. and Shykhoun, M. (1988) Evaluation of farm resource management in the north-west coast of Egypt. In: *Proceedings of Workshop for the Northwest Coastal Region*. Alexandria/Mersa Matrough, Egypt, April 1988. ARC-SWRI/ICARDA-FRMP.

Ennabli, N. (1993) *Les Amenagements Hydrauliques et Hydro-Agricoles en Tunisie*. Institut National Aronomique de Tunis, Tunisia.

Evenari, M., Shanan, L. and Tadmor, N.H. (1968) 'Runoff farming' in the desert. I. Experimental layout. *Agronomy Journal* 60, 29–32.

Evenari, M., Shanan, L. and Tadmor, N.H. (1971) *The Negev, the Challenge of a Desert*. Harvard University Press, Cambridge, Massachusetts, USA.

Falkenmark, M., Fox, P., Persson, G. and Rockström, J. (2001) *Water Harvesting for Upgrading of Rainfed Agriculture: Problems Analysis and Research Needs*. Stockholm International Water Institute, Stockholm, Sweden.

FAO (Food and Agriculture Organization of the United Nations) (1994) *Water Harvesting for Improved Agricultural Production*. Proceedings of the FAO Expert Consultation, Cairo, Egypt, 21–25 November 1993. Water Reports 3. FAO, Rome, Italy.

FAO (Food and Agriculture Organization of the United Nations) (2001) *Water Harvesting in Western and Central Africa*. RAF/Publication, FAO, Rome, Italy.

Frasier, G.W. and Myer, L.E. (1983) *Handbook of Water Harvesting*. Agricultural Handbook No. 600. US Department of Agriculture, Agricultural Research Service, USA.

Hatibu, N., Mutabazi, K., Senkondo, E.M. and Msangi, A.S.K. (2006) Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. *Agricultural Water Management* 80, 74–86.

Joshi, P.K., Jha, A.K., Wani, A.P., Joshi, L. and Shiyani, R.L. (2005) Meta-analysis to assess impact of watershed program and people's participation. *Comprehensive Assessment of Water Management in Agriculture*. Research Report 8. IWMI, Colombo, Sri Lanka.

Kolarkar, A.S., Murthy, K. and Singh, N. (1983) Khadin – a method of harvesting water for agriculture in the Thar desert. *Journal of Arid Environment* 8, 59–66.

Kutsch, H. (1983) Currently used techniques in rainfed water-concentrating. *Applied Geography and Development* 21, 108–117.

Li, F., Cook, S., Geballe, G.T. and Burch, W.R. Jr (2000) Rainwater harvesting agriculture: an integrated system for water management on rainfed land in China's semi-arid areas. *AMBIO* 29(8), 477–483.

Nasri, S. (2002) Hydrological effects of water harvesting techniques. PhD thesis, Department of Water Resources Engineering, Land Institute of Technology, Sweden.

Oweis, T. and Taimeh, A. (1996) Evaluation of a small basin water-harvesting system in the arid region of Jordan. *Water Resources Management* 10, 21–34.

Oweis, T. and Taimeh, A. (2001) Farm water-harvesting reservoirs: issues of planning and management in dry areas. In: Adeel, Z. (ed.) *Integrated Land Management in Dry Areas*. Proceedings of a Joint UNU–CAS International Workshop, Beijing, China, 8–13 Sept 2001. UNU, Tokyo, Japan, pp 165–182.

Oweis, T., Hachum, A. and Kijne, J. (1999) *Water Harvesting and Supplemental Irrigation for Improved Water Use Efficiency in the Dry Areas*. SWIM Paper 7. International Water Management Institute (IWMI), Colombo, Sri Lanka.

Oweis, T., Prinz, D. and Hachum, A. (2001) *Water Harvesting: Indigenous Knowledge for the Future of the Drier Environments*. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Oweis, T., Hachum, A. and Bruggeman, A. (eds) (2004) *Indigenous Water Harvesting Systems in West Asia and North Africa*. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Pacey, A. and Cullis, A. (1986) *Rainwater Harvesting: the Collection of Rainfall and Runoff in Rural Area*. IT Publications, London, UK.

Perrier, E.R. (1988) Opportunities for the productive use of rainfall normally lost to cropping for temporal or spatial reasons. In: Bidinger, F.R. and Johansen, C. (eds) *Drought Research Priorities for the Dryland Tropics*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Prinz, D. (1996) Water harvesting – past and future. In: Pereira, L.S. (ed.) *Sustainability of Irrigated Agriculture*. Proceedings of NATO Advanced Research Workshop, Vimiero, 21–26 March 1994. Balkeman, Rotterdam, the Netherlands, pp. 135–144.

Rees, D.J., Qureshi, Z.A., Mehmood, S. and Raza, S.H. (1991) Catchment basin water harvesting as a means of improving the productivity of rain-fed land in upland Balochistan. *Journal of Agricultural Science, Cambridge* 116, 95–103.

Reij, C., Mulder, P. and Begemann, L. (1988) *Water Harvesting for Plant Production*. Technical Paper No. 91. World Bank, Washington, DC, USA.

Rockström, J., Barron, J. and Fox, P. (2001) Rainwater management for increased productivity among smallholder farmers in drought prone environments. In: *Proceedings of the 2nd WARFSA/WaterNet Symposium 'Integrated Water Resources Management: Theory, Practice, Cases'.* Cape Town, UNESCO, 30–31 October 2000, pp. 319–330.

Rodriguez, A., Shah, N.A., Afzul, M. and Mustafa, U. (1996) Is water-harvesting in valley floors a viable option for increasing cereal production in Highland Baluchistan, Pakistan? *Experimental Agriculture* 32, 305–315.

Somme, G., Oweis, T., Abdulal, A., Bruggemen, A. and Ali, A. (2004) *Microcatchment Water Harvesting for Improving Vegetative Cover in the Syrian Badia.* On-farm Water Husbandry in WANA Series Report No. 3. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Tadmor, N.H., Evenari, M. and Shanan, L. (1970) 'Runoff farming' in the desert. IV. Survival and yields of perennial range plants. *Agronomy Journal* 62, 695–699.

Tauer, W. and Humborg, G. (1992) *Runoff Irrigation in the Sahel Zone*. Verlag Josef Margraf Scientific Books, FR, Germany.

UNEP (United Nations Environment Programme) (1983) *Rain and Stormwater Harvesting in Rural Areas.* UNEP Report. Tycooly International Publishing, Dublin, Ireland.

Wani, S.P., Joshi, P.K., Raju, K.V., Sreedevi, T.K., Wilson, M., Shah, A., Diwakar, P.G., Palanisami, K., Marimuthu, S., Ramakrishna, Y.S., Meenakshi Sundaram, S.S. and D'Souza, M. (2008) *Community Watershed as Growth Engine for Development of Dryland Areas – Executive Summary.* A Comprehensive Assessment of Watershed Programs in India, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Yuan, T., Fengmin, L. and Puhai, L. (2003) Economic analysis of rainwater harvesting and irrigation methods, with an example from China. *Agricultural Water Management* 60 217–226.

10 Supplemental Irrigation for Improved Rainfed Agriculture in WANA Region

T. Oweis* and A. Hachum

*Integrated Water and Land Management Program, International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria; email: *t.oweis@cgiar.org*

Introduction and Concepts

Historically, the focus of water resource planning and management has been on blue water resources for irrigation, industry and domestic purposes. Water investments in rainfed agricultural areas, which are usually located at the upstream of river basins, are lacking and mostly focus on stream flows, surface run-off generation and rivers' routing. In water-scarce regions, the green water resource (the soil moisture in the plant root zone) makes up 85–90% of the precipitation, reflecting the significant portion of the available freshwater that sustains rainfed agriculture. However, green water use and its monitoring and management have received little attention from engineers, planners and policy makers.

About 80% of the world's agricultural land is rainfed, contributing to at least two-thirds of global food production. In sub-Saharan Africa more than 95% of farmed land is rainfed. It is almost 90% in Latin America, 60% in South Asia, 65% in East Asia, and 75% in West Asia and North Africa (WANA) (Rockström *et al.*, 2007). Undoubtedly, irrigation plays a very important role in supplying food. However, the potential for increasing water withdrawals for irrigation is considered quite limited. Despite the higher risks in rainfed agriculture, especially in drought-prone areas, it is widely accepted that the bulk of world food will continue to come from rainfed agriculture.

Irrigation accounts for about 72% of global and 90% of developing-country water withdrawals. Water availability for irrigation may have to be reduced in many regions in favour of rapidly increasing non-agricultural water uses in industry and households, as well as for environmental purposes. However, rainfed areas currently account for about 60% of world food production. Given the importance of rainfed cereal production, insufficient attention has been paid to the potential of production growth in rainfed areas to play a significant role in meeting future food demand. This potential could be realized through adoption of improved management options on a large scale. Farmers' yields in rainfed regions in the developing countries are low largely due to low rainwater use efficiency because of inappropriate soil, water, nutrient and pest management options, lack of seeds of improved cultivars and poor crop establishment. There is a large untapped potential of rainfed agriculture, especially in Asia and Africa, where the bulk of the world's poor live. Lack of clear and sound water policy in rainfed agriculture is among the reasons for the low yield and water productivity in these areas (Rockström *et al.*, 2007, Wani *et al.*, 2008).

There are three primary ways to enhance rainfed agricultural production, namely: (i) to

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

increase the effective rainfall use through improved water management; (ii) to increase crop yields in rainfed areas through agricultural research; and (iii) through reformed policies and increased investment in rainfed areas. This chapter focuses on the first way, in which supplemental irrigation (SI) plays a major role in increasing water use efficiency and yields of rainfed crops.

Rainfed environment

The climate of the rainfed dry areas (arid, semi-arid, dry subhumid) is characterized by complex climatic deficiencies, manifested as agricultural water scarcity for rainfed crop production. The rainfall amount, as well as distribution, is not in favour of stable and satisfactory yield. Rainfall is highly unreliable, with strong risks of dry spells during the crop growth season, even during good rainfall years. Interannual and spatial fluctuations of rainfall are high.

Within the dry areas of WANA, because rainfall amounts and distribution are usually suboptimal, moisture-stress periods often occur during one or more stages of crop growth, causing very low crop yields. Variation in rainfall amounts and distribution from one year to another causes substantial fluctuations in production, which can range, in the case of wheat for example, from 0.3 to over 2.0 t/ha. This situation creates instability and negative socio-economic impacts. Even for breeding modern varieties for rainfed areas, the high heterogeneity and erratic rainfall of rainfed environments make plant breeding a difficult task.

Reasons for low rainfall water productivity

Poverty, drought, low soil fertility and land degradation are the major factors for low rainfall productivity that are challenging the rainfed agriculture in the dry areas (Rockström *et al.*, 2007; Wani *et al.*, 2008). Another reason for low yields in the stressed environments of rainfed areas is soil deficiency in terms of soil infiltration and soil water-holding capacity: all the rainfall does not infiltrate and/or not all that infiltrates is beneficially utilized. Improper cultivars, which are basically bred to withstand drought under irrigated conditions and poor production inputs, such as poor land preparation and lack of fertilizers, are among other reasons for low rainfed production. Widespread deficiency of micro- and secondary nutrients such as zinc, boron and sulfur, in addition to organic carbon and macronutrient deficiencies, are largely holding back the potential of rainfed areas (Rego *et al.*, 2007; Sahrawat *et al.*, 2007).

Globally, 69% of all cereal area is rainfed. Worldwide, rainfed cereal yield is about 2.2 t/ha, which is about 65% of the irrigated yield (3.5 t/ha). The importance of rainfed cereal production is partly due to the dominance of rainfed agriculture in developed countries. More than 80% of the cereal area in developed countries is rainfed. The average rainfed cereal yield in developed countries is as high as irrigated cereal yields in developing countries. Irrigation is relatively more important in cereal production in developing countries, with nearly 60% of future cereal production in developing countries coming from irrigated areas. However, rainfed agriculture remains important in developing countries as well. Rainfed yield in developing countries is around 1.0–1.5 t/ha, which is two- to fourfold less than that of the achievable potential yield on commercial/researcher-managed plots (Rockström *et al.*, 2007; Wani *et al.*, 2008).

Lack of investment in rural infrastructure and poor water policies are among the reasons for the dramatic gap between potential yields in rainfed areas and the actual yields achieved by farmers. Important policies should include higher priority for rainfed areas in agricultural extension services and access to markets, credit and input supplies. Investment in rainfed areas, policy reform and transfer of technology such as SI and water harvesting requires coordinating efforts among all players, including agricultural researchers, local organizations, farmers, community leaders, non-governmental organizations (NGOs), national policy makers and donors.

Supplemental irrigation as a response

Shortage of soil moisture in the dry rainfed areas often occurs during the most sensitive growth stages (flowering and grain filling) of the crops.

As a result, rainfed crop growth is poor and yield is consequently low. Supplemental irrigation, using a limited amount of water, if applied during the critical crop growth stages, can result in substantial improvement in yield and water productivity. Therefore, SI is an effective response to alleviate the adverse impact of soil moisture stress during dry spells on the yield of rainfed crops. Supplemental irrigation may be defined as 'the addition of small amounts of water to essentially rainfed crops during times when rainfall fails to provide sufficient moisture for normal plant growth, in order to improve and stabilize yields' (Oweis and Hachum, 2003). By this definition, and since rainfall is the major water supply source for crop growth and production, the amount of water added by SI cannot by itself support economical crop production. In addition to yield increases, SI also stabilizes rainfed crop production (Oweis and Hachum, 2003).

Unlike full irrigation, in which the crop depends mainly on artificial irrigation since the rainfall amount is very limited, the timing and amount of SI cannot be determined in advance, owing to rainfall stochasticity. Supplemental irrigation in rainfed areas is based on the following three basic aspects (Oweis, 1997):

1. Water is applied to a rainfed crop that would normally produce some yield without irrigation.
2. Since rainfall is the principal source of water for rainfed crops, SI is only applied when rainfall fails to provide essential moisture for improved and stable production.
3. The amount and timing of SI are scheduled not to provide moisture-stress-free conditions throughout the growing season but to ensure that a minimum amount of water is available during the critical stages of crop growth, which would permit optimal instead of maximum yield.

Harvest results from farmers' fields showed substantial increases in crop yield in response to the application of relatively small amounts of irrigation water. This increase covers areas with low as well as high annual rainfall. The area of wheat under SI in northern and western Syria (where annual rainfall is greater than 300 mm) has increased from 74,000 ha (in 1980) to 418,000 ha (in 2000), an increase of 470%. Estimated mean annual increase in production cost due to SI (including fixed and variable costs) as compared with rainfed equals US$150 per hectare. Estimated mean increase in net profit between rainfed and SI for wheat equals US$300 per hectare. The ratio of increase in estimated annual net profit per hectare to estimated difference in annual costs between rainfed and SI is 200%, which is high (Oweis and Hachum, 2006a).

Source of water for supplemental irrigation

Probably the first aspect that comes to mind when planning SI for rainfed agriculture in dry areas is the source of water for irrigation. In a developed river basin with full irrigation for the summer crops and rainfed for winter crops (such as in WANA countries characterized by Mediterranean climate), the same water source and irrigation facilities are used for SI. One good example of such a case is the North Jazirah Irrigation Project in Nineva Province, northern Iraq, in which 25% of the 60,000 ha project area is cultivated under full irrigation in summer and 75% of the area is under rainfed wheat with SI in winter (Adary *et al.*, 2002). The source of water for the project is the River Tigris.

Groundwater is the most common source of water for SI. In Syria, for example, groundwater represents 60% of all water used in irrigation. In many dry regions, more than 90% of the supplemental-irrigated rainfed areas are fed from groundwater. However, the problem of using groundwater for irrigation in the dry areas is the overexploitation of this natural resource. Pumping groundwater in excess of the natural recharge of water to the aquifer endangers sustainability of the development, which depends on this water. Thousands of wells in the region are drying out each year. Groundwater mining in the dry areas is a serious problem that must be carefully considered, taking into account the quantity and quality as well as legal and institutional aspects.

Water harvesting could be very useful in providing the water needed for SI to upgrade the productivity of rainfed crops grown under marginal environments characterized by low and highly variable rainfall. In this case, run-off water is collected into a surface or subsurface storage facility for later use as a water supply source for SI. In sub-Saharan Africa and other tropical semi-arid areas, rainwater harvesting, which collects surface run-off, is used to provide most water for SI. Although seasonal rainfall in these environments is higher than around the Mediterranean, its effectiveness is low because of higher evaporation losses and lower soil water-holding capacity at the root zone.

Water often flows in temporary (ephemeral) streams called *wadi* and could be stored in surface or subsurface reservoirs. Water storage is important when ephemeral flows are not available or run low, at the time when irrigation water is most needed. Surface storage could be small dams, ponds and man-made tanks or small-scale reservoirs in which the source of water is usually ephemeral or intermittent flows in *wadis* or valleys (Oweis *et al*., 1999). Several issues, both technical and socio-economic, need to be considered for optimal implementation of this water-harvesting system. There are many scenarios for the management of the water-harvesting reservoir for SI (Oweis and Taimeh, 2001). One scenario is to empty the reservoir as soon as possible after it is filled and water is stored in the soil profile to save water that otherwise would be lost by evaporation and to ensure reservoir space for the next run-off. More water can be stored and utilized but the risk of not having additional run-off after emptying the reservoirs is real. Bridging dry spells through SI of rainfed crops using harvested rainwater can be an interesting option to increase the yield and water productivity (Oweis *et al*., 1999).

In water-scarce areas, farmers use marginal-quality water resources for SI. Whether beneficially used or wasted, marginal-quality water needs appropriate treatment and disposal in an environmentally feasible manner. The protection of public health and the environment are the main concerns associated with such wastewater reuse. The use of saline and/or sodic drainage and brackish groundwater resources is increasing and warrants attention in order to cope with the inevitable increases in salinity and sodicity that will occur. Agricultural drainage water is becoming an appealing option for many countries, not only to protect natural resources from deterioration but also to make a new water resource available for agriculture. In Egypt, the total reused drainage water is now approximately 7.2 billion m^3/ year, some 12% of total water resources available to Egypt. Treating these drainage waters as a 'resource' rather than as a 'waste' contributes to the alleviation of water scarcity, environment protection and sustainability of agricultural production systems.

Supplemental Irrigation Impact on Rainfed Agriculture

Productivity increases

Research results from the International Center for Agricultural Research in the Dry Areas (ICARDA) and other institutions in the dry areas, as well as harvest from farmers, showed substantial increases in rainfed crop yields in response to SI application in low as well as high rainfall regions.

Supplemental irrigation caused rainwater productivity in north-west Syria to increase from 0.84 kg of grain/m^3 of water (for rainfed) to 1.53 kg of grain/m^3 of water (at one-third SI), 2.14 kg grain/m^3 of water (at two-thirds SI) and 1.06 kg grain/m^3 of water (at full SI). Similarly, for biomass water productivity, the obtained mean values are 2.37, 2.42, 3.9 and 2.49 kg grain/m^3 of water for rainfed, one-third SI, two-thirds SI and full SI, respectively. The results show more significant improvement in SI water productivity at medium SI application rates than at full SI. Highest water productivity was achieved at rates between one-third and two-thirds of full SI. Water productivity becomes an issue for farmers only if water is the production factor that most constrains yields or if saving water yields immediate benefits. Guidelines for recommending irrigation schedules under normal water availability conditions need to be revised when applied in water-scarce areas.

In Syria, average wheat yield under rainfed conditions is only 1.25 t/ha, and this is one of the highest in the region. With SI, the average grain yield was up to 3 t/ha. In 1996, over 40% of rainfed areas were under SI and over half of the 4 million t national production was attributed to this practice. Supplemental irrigation not only increases yield but also stabilizes farmers' production (Oweis and Hachum, 2003).

The average water productivity (i.e. water use efficiency) of rain in producing wheat in the dry areas of WANA ranges from about 0.35 to 1.00 kg grain/m^3 of water. However, water used in SI can be much more efficient. ICARDA found that 1 m^3 of water applied at the right time (when crops suffer from moisture stress) and good management could produce more than 2.5 kg of grains over the rainfed production. This extremely high water use efficiency is mainly attributed to the effectiveness of a small amount of water in alleviating severe moisture stress during the most sensitive stage of crop growth. This stress usually causes a collapse in the crop development and seed filling and reduces the yields substantially. When SI is applied before such conditions occur, the plant may reach its high potential.

When compared with the productivity of water in fully irrigated areas (rainfall effect is negligible), greater advantage is obtained with SI. In fully irrigated areas with good management, wheat grain yield is about 6 t/ha using a total amount of 800 mm of water. This makes water productivity about 0.75 kg grain/m^3 of water, one-third of that under SI with similar management. Under purely rainfed conditions, the rainwater productivity, however, is only 0.5 kg grain/m^3 of rainwater (Oweis, 1997). This suggests that water resources are better allocated to SI when other physical and economic conditions are favourable.

Deficit supplemental irrigation

Deficit irrigation is an optimizing strategy by which crops are deliberately allowed to sustain some degree of water deficit and yield reduction in order to maximize the productivity per unit of water used. One important merit of deficit supplemental irrigation is the greater potential for benefiting from unexpected rainfall during the growing season owing to the availability of larger storage space in the crop root zone. Results on wheat, obtained from farmers' field trials conducted in a Mediterranean climate in northern Syria, reported significant improvement in SI water productivity at lower application rates than at full irrigation as discussed above.

In northern Syria, water-short farmers apply half the amount of full SI water requirements to their wheat fields. By doing so, the area under SI is doubled using the same amount of water, and total farm production increases by 33%. Research in the WANA region has shown that applying only 50% of full SI requirements causes yield reduction of only 10–15%. A farmer having a 4-ha farm would on average produce 33% more grains from his farm if he adopted deficit irrigation for the whole area than if the full irrigation were applied to half of the area (Fig. 10.1).

In the highlands of WANA region, frost occurs between December and March, turning field crops dormant. Usually, the first rainfall sufficient to germinate seeds comes late, resulting in a small crop stand when the frost occurs in December. Rainfed yields, as a result, are much lower than anticipated from a good crop stand pre-frost by early sowing in December and applying 50 mm of SI in October. Application of 50 mm of SI to wheat sown early has increased grain yield by more than 60%, adding more than 2 t/ha to the average rainfed yield of 3.2 t/ha (Ilbeyi *et al.*, 2006). Water productivity reached 4.4 kg grain/m^3 of consumed water compared with water productivity values of wheat of 1–2 kg grain/m^3 of water under traditional practices.

The mean grain yield for the barley genotypes under Mediterranean climate with total rainfall of 186 mm was 0.26 t/ha for rainfed, 1.89 t/ha for 33% SI, 4.25 t/ha for 66% SI, and 5.17 t/ha for 100% SI. The highest yields of one of the genotypes (Rihane-3) were 0.22, 2.7, 4.75 and 6.72 t/ha for the four SI levels, respectively. These dramatic results under SI were obtained partly because of the drought during this season (ICARDA, 1989).

Northern Iraq is a typical rainfed area in WANA (from 300 to 500 mm seasonal rainfall with non-uniform temporal and spatial distribution). Huge investments in SI systems and infrastructure were made to overcome rainfall shortages. Substantial improvement is made in yield and water productivity in using SI in conjunction with proper production inputs and system management (Adary *et al.*, 2002). In the growing season of 1997/98 (annual rainfall 236 mm), rainfed wheat yield in one of the irrigation projects increased from 2.16 t/ha to 4.61 t/ha by applying only 68 mm of irrigation water at the critical time. Application of

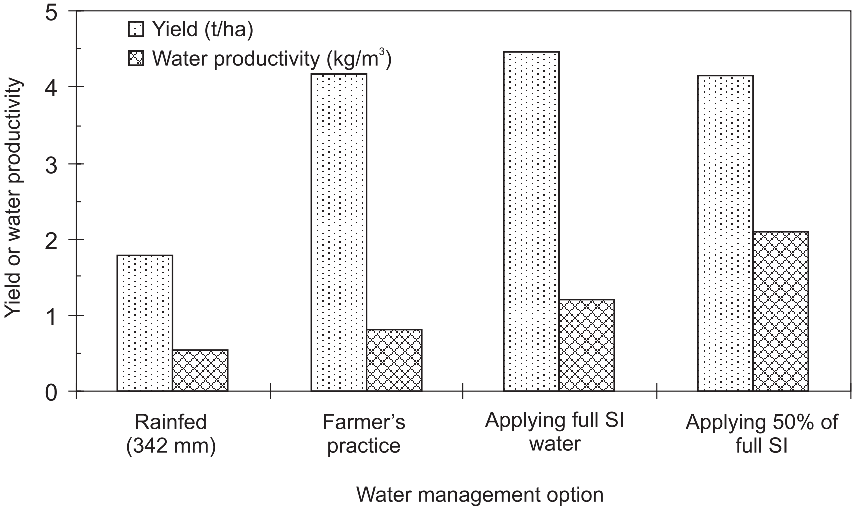


Fig. 10.1. Yield and water productivity for wheat under different water management options for a 4-ha farm in northern Syria (after Oweis and Hachum, 2006b).

100–150 mm of SI in April and May gave maximum results.

In the winter rainfall environment of WANA region, delaying the general sowing date retards crop germination and seedling establishment because of the rapid drop in air temperature starting generally in November. Every week delay after this time results in a 200–250 kg/ha yield decrease. With SI, it is possible to decide on the sowing date of the basically rainfed crops without the need to wait for the onset of seasonal rain, with a longer growing season and earlier maturity, which helps the crop to escape terminal drought.

Analysis of 4 years' data (1996–2000) of SI on winter-sown food legumes observed at ICARDA's fields in northern Syria under different water management options has shown significant improvement in yield and water productivity for chickpea, lentil and faba bean (Oweis and Hachum, 2003). However, lentil and faba bean are more responsive to SI than chickpea (Table 10.1).

Potential of Supplemental Irrigation in WANA

The governing factor when considering the potential of SI in rainfed semi-arid areas is the availability of water (blue water) to supplement rainfall in supporting the basically rainfed crop. In many dry areas, there are at least two growing seasons: a dry season (with negligible rainfall) such as summer in the Mediterranean, during which full irrigation is needed, and a wet rainy season such as winter in the Mediterranean, in which the amount and distribution of rainfall are not in favour of desired crop production. All irrigation schemes in such areas are used for full

Table 10.1. Water productivity (kg grain/ha/mm) for three legume crops under rainfed and 100% supplemental irrigation at Tel Hadya, northern Syria.

Crop	Rainfed (SI=0)[a]	100% SI[a]	Source of data
Chickpea	4.2	4.3	Oweis *et al.*, 2004a
Lentil	4.0	5.1	Oweis *et al.*, 2004b
Faba bean	5.6	6.2	Oweis *et al.*, 2005

[a] Means of four growing seasons (1996–2000).

irrigation in summer and SI in winter. In this section, summaries of two case studies, one in Syria and another in Tunisia, for assessing the potential of SI are presented.

The case of Syria

The irrigation water discharge available (from surface or groundwater) in existing irrigation schemes that are being used to fully irrigate summer crops, within the rainfed proximity, can be used in winter for SI of winter crops. Since water requirements for SI are a fraction of those for full irrigation, the areas that can be irrigated in winter are much larger than areas currently used for full irrigation in summer. The method uses a combination of a simple model to calculate the additional rainfed area that can be partially irrigated by the possible water savings made by the shift from spring/summer fully irrigated crops to supplementally irrigated winter/spring crops, with a water-allocation procedure for the surrounding rainfed areas based on suitability criteria. In case of water scarcity, some shift (reallocation) may be made from the normally less-efficient full irrigation in summer to highly efficient winter SI.

To assess the impact of adopting SI of winter–spring crops over that of using water only for fully irrigated summer crops, two steps are needed. The first is to estimate the water savings that could be achieved, first within each area unit (pixel) of the irrigated area, and then the total savings for the irrigated area or for a specified fraction of the area. The second is to distribute these water savings among pixels that at present are not irrigated but meet specified criteria. The criteria used were based on distance from the irrigated perimeter, slope, soils and presence of forests. The scores obtained against these four criteria were combined in a multi-criteria evaluation using the principle of the most limiting factor.

Distribution rules need to be established that emulate *allocation priorities*. A simple distribution rule would be one in which those pixels that score best against the different criteria are filled up first, followed by those that score less well, etc. A second distribution rule could be to fill up the pixels in accordance with the allocation priorities established by Rule 1 with a user-specified fraction of the water requirement that is not met by precipitation (Rule 2). Further rules could be put in place but Rules 1 and 2 are sufficiently powerful to simulate fairly complex realities.

By integrating existing information, derived from either thematic maps or satellite imagery, in a GIS (geographical information system), this procedure for calculating water savings and reallocating them for SI is carried out in the case of Syria (De Pauw *et al.*, 2006). In a district with mean long-term annual rainfall of 360 mm, the net crop water requirement for cotton turns out to be 1056 mm, while for wheat it is only 154 mm. This simply means that in this locality, one can potentially grow 7 ha of wheat (under SI) using the same water needed for growing 1 ha of cotton (under full irrigation). However, a lot of technical and economical efforts and inputs need to be considered for its feasibility.

The case study indicated that, in most of the irrigation districts, water saved by shifting from the dry season to the wet season is only partially depleted for SI due to poor soils, topography or distance constraints or SI is basically not needed due to enough rainfall in the area. The ratio of the water depleted to the water saved, called Usable Water Saving Ratio (UWSR), indicates to what extent this condition exists. At the same time it answers the question of what percentage of an irrigation scheme can potentially shift from full irrigation to SI. The UWSR ranged from zero to one.

From this case study, it appears that in Syria a large potential for SI exists by way of shifting from a fully irrigated summer crop to a partially irrigated winter–spring crop. Roughly this potential amounts to more than doubling of the area currently under SI.

The case of Tunisia

In water-scarce areas, traditional options based on full irrigation with intensive cropping systems are not the relevant choices anymore because of chronic water shortages.

In Tunisia, as in other Maghreb countries, rainfall is almost the only source of fresh water. Mean annual precipitation ranges from 1500 mm on the peaks of the mountains in the most north-western corner of the country to less than 100 mm in the south. Precipitation variability in time is also very high, both within and between years. Out of a total land area of 155,000 km^2, the non-arid area is estimated at 37,000 km^2 (24%), the arid at 55,000 km^2 (35%) and desert at 63,000 km^2 (41%). Hence, the mean total precipitation is 36 km^3, out of which only 3 km^3 could be potentially collected as run-off water in large dams. Renewable groundwater resources are estimated at 1.8 km^3. The ratio of potentially irrigable land to arable land is as low as 9%, reflecting the scarcity of water in the country. Hence, most agricultural systems are based on dry farming with cereals and olive tree cultivation as dominant activities.

In Tunisia, potential areas for developing SI are identified by taking advantage of the available experience in implementing small hill reservoirs to collect water for SI. Existing structures are used as a starting point for a methodological development for mapping the potential site for harnessing run-off water. Concerning soils, a capability index for irrigation was calculated for each soil unit reported in the descriptive soil map of Tunisia. Regional suitability for SI is obtained by an overlay of the two potential maps.

Diverse options are available for SI implementation, which could be applied in large-scale irrigation perimeters based on large dams and conveyance systems or in small-scale irrigation from shallow wells or small reservoirs where run-off water is collected. Hill reservoirs or lakes have been recently developed with the objective of collecting surface run-off from the catchment area and storing it in small surface reservoirs in order to give access to water for farmers in remote areas. With watersheds of few hundred hectares, excess rainwater not allocated during the rainy season is diverted to storage in ponds and apportioned for irrigation purposes. The average reservoir capacity varies, typically between 10,000 and 200,000 m^3, and the run-off catchment area ranges from 40 to 700 ha (Ben Mechlia *et al.*, 2006).

Unlike large reservoirs, hill lakes are not permanent sources of water and their management is very site specific. Farmers ensure that they have all the water needed and decide on the area that should be put under SI during winter. By the end of the winter season, i.e. in March, the state of the reservoir is of particular interest if late spring or summer irrigation is planned for vegetable crops. A survey conducted during a wet year showed that total water used was on average equivalent to 80% of the capacity of reservoirs.

Suitability of lands for agriculture land capability is related to their potential for making water and nutrients available to plants and it is based on using existing soil information and a Digital Elevation Model (DEM) for mapping land suitability for surface irrigation. The success of SI depends on the availability of appropriate infrastructure for implementing irrigation programmes within areas of productive lands.

Rainfall amount, watershed area and mean slope determine the run-off water that can be stored in a hill reservoir. However, the determination of the size of the reservoir and its location depends on technical, socio-economic and environmental factors and constraints. When determining the potential for run-off water collection in hill reservoirs, only physical factors could be taken into account. A methodology to map areas suitable for hill reservoirs is developed and implemented in the assessment of SI potential in Tunisia. It involves four steps: (i) identification of existing hill reservoirs from satellite images and determination of their watershed areas from DEMs; (ii) determination of typical size and slope of identified watersheds; (iii) deriving potential sites for hill reservoir construction in the pilot area; and (iv) validation of the methodology.

Practices such as SI and regulated deficit irrigation have the potential to increase productivity and to reduce environmental risk. Full irrigation with intensive cropping systems is not a viable approach in this environment and is probably no longer sustainable, considering the prevailing constraints including investment costs and land degradation.

Economics of Supplemental Irrigation

Increase in crop production per unit of land or per unit of water does not necessarily increase farm profit, just because of the nonlinearity of crop yield with production inputs, particularly with water and its interaction with other input factors. Therefore, a water management strategy that maximizes yield or water productivity is not necessarily the most desirable one, especially in water-scarce areas. Often such a strategy is not the most economical in terms of net return. Actually, the most desirable strategy is somewhere in between these two. In northern Syria, the increase in wheat grain yield due to SI under different annual rainfall is depicted in Fig. 10.2. The levels of SI water to which the crops could be underirrigated without reducing income below that which would be earned for full SI under limited water resources is the best bet. For sustainable utilization of water resources and higher water productivity, the recommendation to SI practitioners under limited water resource conditions is to adopt the scenario that maximizes the profit. For the case depicted in Fig. 10.1, this scenario results in a sub-maximum (but economically optimal) grain yield of 4–5 t/ha.

Since rainfall amount cannot be controlled, the optimal amount of SI that results in maximum net benefit to the farmers is determined. Knowing the cost of irrigation water and the expected price for a unit of the product, Fig. 10.3 helps in deciding on the optimal amount of SI to be applied under different rainfall zones and various price ratios. This simplified procedure of Figs 10.2 and 10.3 could be developed for any other locality having different rainfall amounts, input costs and product prices.

Farmers in developing countries seldom have the means to monitor soil water depletion. Schedules based on soil moisture tension in the active root zone are useful, but the farmers are unable to use either due to lack of know-how or unavailability of equipment. Methods based on soil water measurements and on plant-stress indicators present some difficulties, particularly for farmers. Tensiometers and plant indicators provide information on the irrigation date only. The farmer still needs information on how much water to apply. Farmers are always criticized for being wasteful and applying excessive water. Actually, the root cause of this inefficient practice is that the farmer does not know how to measure water flow or quantity, and therefore he is applying more than what is needed in order to be on the safe side.

Maximizing Supplemental Irrigation Benefits

Improving soil fertility

Supplemental irrigation alone, although it alleviates moisture stress, cannot ensure highest performance of the rainfed agricultural system. It has to be combined with other good farm

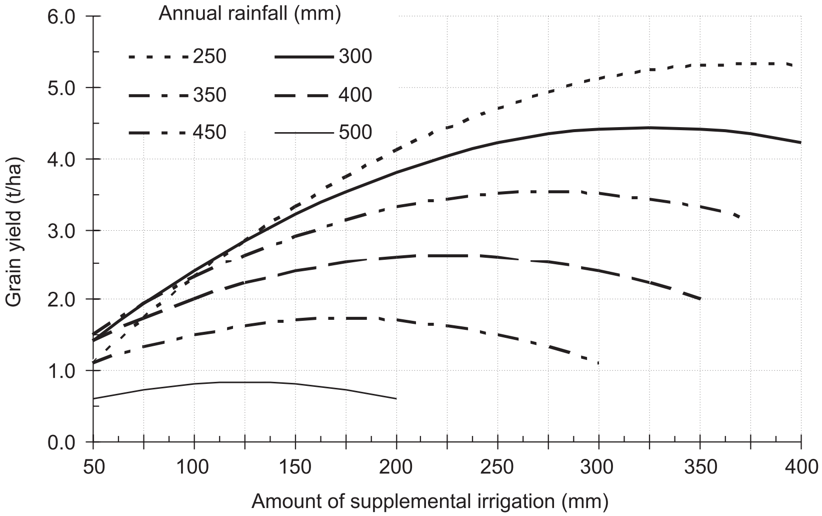


Fig. 10.2. Supplemental irrigation production functions for rainfed wheat in northern Syria under different levels of rainfall (after Oweis and Hachum, 2006b).

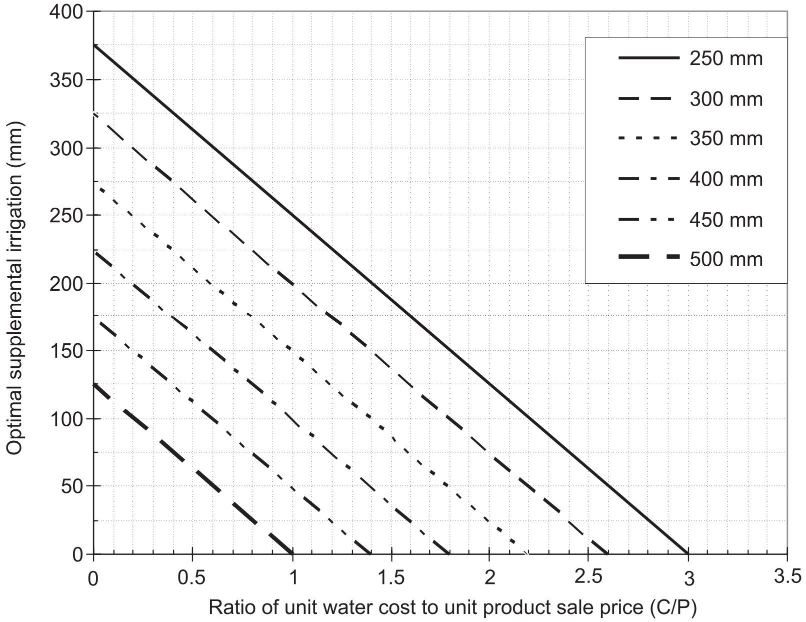


Fig. 10.3. Supplemental irrigation (SI) optimization chart for rainfed wheat in northern Syria under different levels of rainfall (Source: Oweis and Hachum, 2006b).

management practices. Of utmost importance is soil fertility, particularly in the Mediterranean region, where nitrogen deficiency is usually the main issue. Absence of nutrient deficiency greatly improves yield and water use efficiency. Other areas may have different deficiency levels of nitrogen or deficiencies in other elements (Table 10.2). It is always important to eliminate these deficiencies to get potential yield and water productivity. Yield, especially biological, significantly increased with the increase in nitrogen fertilizer, and farmers were strongly advised to continuously monitor the nitrogen level in the soil for economical and environmental reasons.

Research in Burkina Faso and Kenya has shown that SI of 60–80 mm can double, and even triple, grain yields from the traditional 0.5–1 t/ha (sorghum and maize) to 1.5–2.5 t/ha. However, most beneficial effects of SI were obtained only in combination with soil fertility management. The major constraint to SI development in Africa is farmers' capacity, both technical and financial, to develop storage systems for run-off water (Rockström *et al.*, 2003).

Table 10.2. Gains in water productivity for wheat grain under rainfed and supplemental irrigation with different levels of nitrogen in northern Syria (Source: Oweis and Hachum, 2003).

Nitrogen application rate (kg N/ha)	Water productivity (kg grain/m^3)	
	Rainfed water	Irrigation water
0	0.54	0.81
50	0.89	1.41
100	0.84	2.14
150	0.81	1.40

Appropriate sowing dates

One of the practical cases of SI is that all the fields may need irrigation at the same time in spring. This case happens when, during the growing season, a rain event with sufficient amount capable of filling the root zone in the entire farm to field capacity occurs. The situation calls for a very high water supply and a large irrigation system. A staggered-sowing strategy reduced the peak farm water demand rate by more than 20%, thus potentially allowing a reduction in the irrigation system size and cost (Oweis and Hachum, 2001). Also, the water demand of a larger area can be met with the same water supply.

Improved cultivars

To get the best out of SI, the proper water-responsive cultivars need to manifest a strong response to limited water applications, which means that they should have a relatively high yield potential. At the same time, they should maintain some degree of drought resistance, and hence express a good plasticity.

Using both traditional breeding techniques and modern genetic engineering, new crop varieties can be developed that can increase the water use efficiency while maintaining or even increasing the yield levels. For example, through breeding, winter chickpea and drought-resistant barley varieties that use substantially less water have been developed. The chickpea crop is traditionally sown in spring. Consequently, terminal drought stress occurs, causing low yields. This was avoided by early planting with cold-tolerant cultivars developed by ICARDA. On-station as well as on-farm trials have demonstrated that increases in yield and water productivity of 30–70% are possible by adopting early sowing. Currently, winter chickpea is spreading fast among the farmers in the WANA region.

Data of farm yield under SI in northern Iraq indicate that SI has more impact on bread wheat varieties as compared with durum varieties. Also SI has increased yield of bread wheat varieties by more than 100%, whereas the increase in yield for the durum wheat varieties ranged between 58 and 81% (ESCWA, 2003).

Efficient supplemental irrigation system

Implementing precision irrigation such as trickle and sprinkler systems, laser levelling and other techniques contributes to substantial improvement in water application and distribution efficiency. Currently, farmers use three major irrigation methods in practice: surface irrigation methods, including basins, furrows and border strips; sprinkler irrigation methods, including set systems, travelling guns and continuous-move systems; and trickle irrigation methods, with drip, micro-sprinklers and subsurface systems. These systems vary greatly in their application, distribution and storage efficiencies.

The major contribution of irrigation systems to improved SI performance is in making water more available in amount and timing for plant growth. The key factor in successful irrigation is the control of water at all times and levels of water conveyance, distribution and field application. For large field crops, a high degree of water control is inherently built in to most of the sprinkler systems owing the nature of this system. Although drip or micro-irrigation systems offer higher levels of water control than the sprinkler system, they are only recommended for trees and row crops. This brings another important factor into the picture of SI system and improved water management, which is *flexibility*. Sprinkling is a flexible irrigation system for several reasons. The top five reasons are: (i) there is no need for land grading or reshaping (which is a basic requirement for successful surface irrigation); (ii) the same system can fit different types of soil and crop; (iii) portability allows the use of the system on many farms at different locations during the same season; (iv) the higher degree of control of water allows the application of small irrigations, which is suitable for SI; and (v) dual uses of the system for other purposes such as chemical application and crop cooling (during summer). A portable sprinkler system can be efficiently used for supplemental irrigation to serve a large cropped area during spring, when the rain is insufficient for the crop, by utilizing a small-flow-rate water source such as a well or a water-harvest pond. This is an important factor in which sprinkler irrigation is superior to surface irrigation in water-short regions.

Although surface irrigation is relatively inexpensive and does not require high technical skill, it is recommended for SI when proper land grading is made to the field or small basins are used. Surface irrigation can be made suitable for SI by using the following techniques:

- *Surge flow irrigation*: by applying water intermittently, instead of continuously, to the furrow, higher distribution uniformity along the run is achieved due to reduced infiltration rate upstream.

- *Wide bed furrows:* partial supply of irrigation water to the cropped land can be useful under deficit irrigation management.
- *Alternate water application to furrows*: irrigating every other furrow in one irrigation cycle and then irrigating the dry furrows skipped in the previous cycle has shown some savings in water application.
- *Level basin:* this is a conventional surface-irrigation method that can achieve very high application efficiency if properly implemented.

Farm water control and measurements

Controlling and quantifying water application requires flow measurement. If water runs off the field, both inflows and outflows must be measured. Flow measurement of canal water supplies is often inadequate or completely lacking. Run-off is seldom measured. Without flow measurement to quantify applications, it is impossible to evaluate the performance of an irrigation practice. Without such evaluations, it is useless to attempt improving the performance of the irrigation services.

An important issue related to SI is the timing of water delivery. Within large irrigation schemes, a farmer has little control on the water distribution among the sectors of the scheme and hence the timing of irrigation water delivery to his farm. This may not match the timing of irrigation and thus adversely affects irrigation scheduling and consequently crop yield and water use efficiency. The on-demand water-delivery system is best suited to SI. This is what small farms use, drawing water from wells or nearby surface water.

Enabling environments

Integrated and participatory research and development (PR&D) programmes offer the best way to bring SI technologies and practices to their full potential. Any development or applied research programme that underestimates the role of farmers is doomed to failure. Acceptance of SI by men and women farmers is a condition for its success. For pilot tests, staff and farmers may select a water basin using agreed criteria. An integrated R&D programme will be designed and implemented in a way that involves local communities, institutions and decision makers. The following issues must be taken into consideration:

- Farmers should see the benefits of a project as early as possible. Motivating and promoting awareness among farmers with regard to the project objectives and the ways to achieve them are essential. Implementation requires commitment and cooperation of neighbouring farmers (or communities) in the coordination and management of their limited water resources.
- The specific needs of a local community or a group of beneficiaries must be understood and designed into an appropriate system, bearing in mind the major role often played by women in agricultural work. Farmers' acceptance of a new technology depends on their attitudes toward production risk. Risk-averse farmers will accept a new technology if they perceive that increased returns would more than compensate for any increase in risk.
- To prevent inequality at the village level from widening as a result of the introduction of SI, special care should be taken to make sure that poor and women farmers have equal access to the technique.
- Most dry-area ecosystems are fragile and do not adjust easily to change. If the introduction of SI changes suddenly the use of, for instance, natural resources, especially land and water, the environmental consequences can be far greater than anticipated.
- The necessary conditions for adoption of new technologies are often location specific because they are influenced by cultural differences, education and awareness of a need for change. Users of land and water resources are usually aware of land degradation, but they may not be able to do anything about it if survival is their primary concern. They are unlikely to take up a new practice unless they are convinced that it is financially advantageous, does not conflict with other activities they consider important, and does not demand too much of their time for maintenance.

- Institutional capacity building, water resources management policies, and management and maintenance programmes are keys to success. Multiple plantings to increase rainfall utilization should become standard practice under SI. Therefore, farmers need to be knowledgeable about water-stress-sensitive growth stages and correct timing of water application.
- Policy reform and public awareness are important issues. Policies related to water use and valuation should be geared towards controlling water use, reducing water demand, safe use and disposal of water, and encouraging the collective approach in using and managing water by users. These policies must be balanced, workable and feasible, otherwise they will be difficult to implement and/or enforce. Policy and institutional aspects of using marginal-quality water in agriculture should examine: the present scenarios to overcome policy and institutional constraints; capacity-building options for the national agricultural and extension systems; and the awareness among the farmers for greater understanding of the potentials of plants, soil and water for the agricultural produce from marginal-quality water (Oweis and Hachum, 2006a).

Demand management and water pricing

Farmers generally tend to over-irrigate. Most SI developments depend on groundwater as a source for irrigation water. Mining groundwater is now a common practice in the region, risking both water reserves and quality. Water demand management in agriculture is the management of water through influencing consumer behaviour by introducing incentives to use water more efficiently. This will involve many elements, such as legislative measures, including a pricing mechanism and financial incentives as well as penalties. It also involves direct technical measures to control and ration water by flow-regulating devices. However, effective public awareness programmes should come at the top of the action list to arrive at fruitful management for water demand. It requires that all users recognize and accept that water supplied to them has a value that varies depending on the purpose of its use. Farmers should understand that the opportunity cost of this water is very high and what they are paying is a small fraction of its real value. Media and extension services can play a role in generating this awareness.

Water pricing is difficult to implement in most of the developing countries. The major reasons for it are not only economic but also cultural and socio-political. Water is seen as a gift of God to humankind and it should be accessible to all. If a pricing mechanism is to be implemented, care must be taken to consider the limited capacity of the resource-poor farmers in addition to other constraints. Effective alternatives to water pricing as a means of demand management are yet to be developed in these countries.

Investment in Supplemental Irrigation

Risk weighs on the daily lives of poor rainfed farmers, and investment packages have to help reduce that risk. Risks include not only climatic and limited access to reliable technology and water but also unstable land tenure and poorly functioning product and credit markets. Investing in SI can have a significant impact on justified returns from dry farming systems. Biophysical returns on water with SI are higher than those under conventional irrigation, and are highest with deficit applications, a powerful message in water-scarce localities. An integrated investment package including water-harnessing and irrigation technology, irrigation scheduling, training, and cropping and fertilizing guidance is probably the best. Combined soil and water management investments can also have a high return. The key requirements for successful investment in SI include:

- Determining the most appropriate scheduling, crops and cropping patterns, and socio-economic feasibility.
- Strong water-user associations with incentives for local communities to use water efficiently.
- Managing the economic and environmental consequences of using water in SI.
- Developing policies that foster an enabling environment for the adoption of water-efficient technologies.

The on-demand water-delivery system is best suited to SI. This is what small farms use, drawing water from wells or nearby surface water. Supplemental irrigation must be properly integrated with other production inputs, including crop and soil management options, improved germplasm and fertilizers to achieve the desired output. Farmers need to understand the technology and how to use it. Extension and human capacity building should play a major role in this respect. Long-term training and advisory programmes should be designed and implemented. It is recommended that practitioners use incentives for farmers' participation, technology transfer and water-cost recovery to prompt adoption of improved management options. In rainfed dry areas, where water is more limiting than land, it is better to maximize yield per unit of water and not yield per unit of land. Inputs other than water and improved cultural practices are also necessary for maximizing profits.

The investment opportunities in SI may focus on reforming policies and regulations to govern groundwater development and operation; strengthening or creating water-user associations; financing water resources development for SI through the source, the conveyance system, and the field-irrigation systems; developing low-cost, low-energy irrigation systems such as drip or sprinkler, including pumping; strengthening extension services; and developing simple and practical tools for SI scheduling.

Conclusions

In rainfed dry areas, where water is more limiting than land, it is better to maximize yield per unit of water and not yield per unit of land. Inputs other than water and improved cultural practices are also necessary for maximizing profits. Supplemental irrigation boosts yield and helps stabilize rainfed agriculture. For the greatest benefit, it must be part of an integrated package of farm cultural practices. Supplemental irrigation that is optimized through on-farm water management policies and timely socio-economic interventions is essential for the sustainable use of limited water resources, particularly groundwater. A water management strategy that maximizes yield or water productivity is not necessarily the most desirable one, especially in water-scarce areas. Actually, the most desirable strategy is somewhere in between these two. Policies related to water use and valuation should be geared towards controlling water use, reducing water demand, safe use and disposal of water, and encouraging the collective approach in using and managing water by users. These policies must be balanced, workable and feasible, otherwise they will be difficult to implement and/or enforce. Integrated and participatory research and development (PR&D) programmes offer the best way to bring SI technologies and practices to their full potential. Investment opportunities in supplemental irrigation may focus on reforming policies and regulations to govern groundwater development and operation, strengthening or creating water-user associations and financing water resources development for SI. Integrated and participatory research and development programmes offer the best way to bring SI technologies and practices to their full potential.

References

Adary, A., Hachum, A., Oweis, T. and Pala, M. (2002) Wheat productivity under supplemental irrigation in northern Iraq. On-Farm Water Husbandry Research Report Series No. 2. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

Ben Mechlia, N., Oweis, T., Masmoudi, M., Anane, M. and Sghaier, N. (2006) Assessment of supplemental irrigation potential in semi arid areas: methodology and a case study from Tunisia. Research Report. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

De Pauw, E., Oweis, T., Nseir, B. and Youssef, J. (2006) Spatial modelling of the biophysical potential for supplemental irrigation: methodology and a case study in Syria. Research Report. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

ESCWA (Economic and Social Commission for Western Asia) (2003) *Enhancing Agricultural Productivity through On-Farm Water Use Efficiency: an Empirical Case Study of Wheat in Iraq.* In collaboration with ICARDA and IPA Agricultural Research Center of Iraq. ESCWA, Beirut, Lebanon.

ICARDA (International Center for Agricultural Research in the Dry Areas) (1989) *Farm Resource Management Program Annual Report for 1989*. ICARDA, Aleppo, Syria.

Ilbeyi, A., Ustun, H., Oweis, T., Pala, M. and Benli, B. (2006) Wheat water productivity and yield in a cool highland environment: Effect of early sowing with supplemental irrigation. *Agricultural Water Management* 82, 399–410.

Oweis, T. (1997) *Supplemental Irrigation: a Highly Efficient Water-use Practice*. ICARDA, Aleppo, Syria.

Oweis, T. and Hachum, A. (2001) Reducing peak supplemental irrigation demand by extending sowing dates. *Agricultural Water Management* 50, 109–123.

Oweis, T. and Hachum, A. (2003) Improving water productivity in the dry areas of West Asia and North Africa. In: Kijne, W.J., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 179–197.

Oweis, T. and Hachum, A. (2006a) Water management in rainfed agriculture – investing in supplemental irrigation. In: *Agricultural Water Sourcebook: Shaping the Future of Water for Agriculture*. The World Bank, Washington, DC, USA, pp. 206–213.

Oweis, T. and Hachum, A. (2006b) Water harvesting and supplemental irrigation for improved water productivity of dry farming systems in West Asia and North Africa. *Agricultural Water Management Journal* 80, 57–73.

Oweis, T. and Taimeh, A. (2001) Farm water-harvesting reservoirs: issues of planning and management in dry areas. In: Adeel, Z. (ed.) *Integrated Land Management in Dry Areas*. Proceedings of a Joint UNU–CAS International Workshop, Beijing, China, 8–13 Sept 2001. UNU, Tokyo, Japan, pp. 165–182.

Oweis, T., Hachum, A. and Kijne, J. (1999) Water harvesting and supplemental irrigation for improved water use efficiency in the dry areas. SWIM Paper 7. International Water Management Institute, Colombo, Sri Lanka.

Oweis, T., Hachum, A. and Pala, M. (2004a) Water use efficiency of winter-sown chickpea under supplemental irrigation in a Mediterranean environment. *Agricultural Water Management Journal* 66, 163–179.

Oweis, T., Hachum, A. and Pala, M. (2004b) Lentil production under supplemental irrigation in a Mediterranean environment. *Agricultural Water Management Journal* 68, 251–265.

Oweis, T., Hachum, A. and Pala, M. (2005) Faba bean productivity under rainfed and supplemental irrigation in Northern Syria. *Agricultural Water Management Journal* 73, 57–72.

Rego, T.J., Sahrawat, K.L., Wani, S.P. and Pardhasaradhi, G. (2007) Widespread deficiencies of sulfur, boron and zinc in Indian semi-arid tropical soils: on-farm crop responses. *Journal of Plant Nutrition* 30, 1569–1583.

Rockström, J., Barron, J. and Fox, P. (2003) Water productivity in rain-fed agriculture: challenges and opportunities for smallholder farmers in drought-prone tropical agroecosystems. In: Kijne, W.J., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 145–162.

Rockström, J., Wani, S., Oweis, T. and Hatibu, N. (2007) Managing water in rainfed agriculture. In: *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Sponsored by Ramsar, CGIAR, FAO and CBD. EarthScan, London, UK, pp. 315–348.

Sahrawat, K.L., Wani, S.P., Rego, T.J., Pardhasaradhi, G. and Murthy, K.V.S. (2007) Widespread deficiencies of sulphur, boron and zinc in dryland soils of the Indian semi-arid tropics. *Current Science* 93(10), 1–6.

Wani, S.P., Joshi, P.K., Ramakrishna, Y.S., Sreedevi, T.K., Piara Singh and Pathak, P. (2008) A new paradigm in watershed management: a must for development of rain-fed areas for inclusive growth. In: Swarup, A., Bhan, S. and Bali, J.S (eds) *Conservation Farming: Enhancing Productivity and Profitability of Rain-fed Areas*. Soil Conservation Society of India, New Delhi, India, pp. 163–178.

11 Opportunities for Water Harvesting and Supplemental Irrigation for Improving Rainfed Agriculture in Semi-arid Areas

P. Pathak,* K.L. Sahrawat, S.P. Wani,*** R.C. Sachan**** and R. Sudi*******

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India;
*emails: *p.pathak@cgiar.org; **k.sahrawat@cgiar.org; ***s.wani@cgiar.org; ****r.sachan@cgiar.org; *****s.r.rao@cgiar.org*

Introduction

Most of the food in the world is produced under rainfed agriculture, which plays a key role in poverty reduction (Rockström *et al.*, 2007). The majority of poor people in the world are dependent on rainfed agriculture for food and income and thus livelihood security (FAO, 2002). The importance of rainfed agriculture varies regionally, but most food for poor communities in the developing countries is produced under rainfed agriculture (Rockström *et al.*, 2007). In rainfed agriculture, water is the key constraint for improving agricultural productivity owing to the extreme variability of rainfall, long dry seasons, recurrent droughts, and floods and dry spells in the same season. In spite of being important for world food security, the investments in rainfed agriculture, particularly in water management, have been neglected since the late 1950s. However, the investments in rainfed agriculture have shown large pay-offs in yield improvements and poverty alleviation through income generation and environmental sustainability (SIWI, 2000; Wani *et al.*, 2003b). This is the conclusion of the Comprehensive Assessment of Water Management in Agriculture, given that rainfed agriculture, particularly in the world's most water-challenged regions, is a risky business, with current yields generally less than half of those in the irrigated systems, where risks due to water shortages are much lower.

The semi-arid tropics (SAT), where rainfall exceeds potential evapotranspiration for 2–4.5 months per year (Troll, 1965), has predominantly rainfed agriculture. Rainfall in the SAT generally occurs in short torrential downpours. A large portion of this water is lost as run-off, eroding significant quantities of precious top soil. The current rainwater use efficiency for crop production is low, ranging from 30 to 55%; thus annually a large percentage of seasonal rainfall is lost as surface run-off, evaporation or deep drainage. Groundwater levels are depleting in the SAT regions, and most rural rainfed areas are facing general water scarcity and drinking water shortages in the summer months. Though the problem of water shortages and land degradation has also been in existence in the past, the pace of natural resource degradation has greatly increased in recent times due to the burgeoning population and the increased exploitation of natural resources. An insight into the rainfed SAT regions shows a grim picture of water scarcity,

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

fragile ecosystems, drought and land degradation due to soil erosion by wind and water, low rainwater use efficiency, high population pressure, poverty, low investments in water use efficiency measures and inappropriate policies (Wani *et al.*, 2003a; Rockström *et al.*, 2007).

Research results from the various institutions/organizations have clearly shown that there is vast potential for improving agricultural productivity in the rainfed SAT. However, the adoption of improved technologies by the resource-poor farmers in the rainfed SAT is limited, primarily due to risk associated with drought. The key challenge is to reduce water-shortage-related risks posed by high rainfall variability rather than coping with an absolute lack of water. There is generally enough rainfall to double and often even quadruple the crop yields in rainfed farming systems, even in the water-constrained regions. But the distribution of rainfall leads to dry spells, and much of the rainwater is lost. Apart from water, upgrading rainfed agriculture requires investments in soil, crop and farm management. However, to achieve these, the rainfall-related risks need to be reduced.

Run-off water harvesting and the use of water for supplemental irrigation is an age-old practice. The critical importance of supplemental irrigation lies in its capacity to bridge dry spells and thereby reduce the risks in rainfed agriculture. Since the late 1960s, considerable research on water harvesting and supplemental irrigation has been conducted across the world, but the literature remains scattered. This chapter discusses the research results and experiences gained in run-off harvesting and supplemental irrigation in the SAT of India and Africa. The current state-of-the-art knowledge about the following seven key aspects of water harvesting and supplemental irrigation is covered in detail:

- Traditional tank irrigation in SAT India.
- Assessment of adequate water availability in tank at critical crop growth stages.
- Optimum tank size and other design parameters.
- Efficient application of supplemental irrigation water.
- Crop responses to supplemental irrigation.
- Economic evaluation of run-off storage structures and supplemental irrigation.
- Watershed-based water harvesting, groundwater recharging and efficient water utilization.

Traditional Tank Irrigation System in SAT India

Water harvesting is an ancient art practised in many parts of northern America, the Middle East, North Africa, China and India. Different indigenous techniques and systems were developed in different parts of the world, and they are still referred to in the literature by their traditional names. Among these are *haffir* and *teru* in Sudan, *gessour* in Tunisia, *khadin* or tank in India, *lacs calinaires* in Algeria, *caag* and *gawans* in Somalia, *sayl* in Yemen, *khuls* in Pakistan and *boqueras* in Spain. Ancient water-harvesting systems are characterized by flexibility and endurance. Flexibility is demonstrated by their easy integration with other resource-use systems as well as their widespread adoption by diverse cultural groups in various parts of the world. Endurance is shown by their antiquity and their capacity to survive situations of abrupt changes in the social order. In India, tank irrigation is one such ancient practice which is still in use in several parts of the country.

In India, tank irrigation is a long-established practice and many tanks are centuries old. Here the ‘tank’ is a small water reservoir behind an earthen dam or a pond excavated out of a field to catch and hold run-off. Tanks are constructed and maintained by irrigation departments (>40 ha command area) and *panchayat* unions (village government). Farmers are responsible for water distribution and management below the outlet. The use of tank-based systems in SAT India is quite widespread. However, the states of Andhra Pradesh and Tamil Nadu contain about 60% of the tank-irrigated area in SAT India. In these states the proportion of tank-irrigated area as a percentage of the total irrigated area has been declining at the rate of 0.3% per year since the late 1970s, largely because of poor management and maintenance. The average tank command area in various districts ranged from 10.3 to 49.1 ha, usually used for paddy rice (Sharma and Helweg, 1982; von Oppen and Subba Rao, 1987).

In a study of 45 tanks grouped according to size, in the Anantapur district in Andhra Pradesh, von Oppen and Subba Rao (1987) found that for small tanks (below 400 ha command area) the ratio of command area to tank bed area was 0.9 while for large tanks (above 400 ha command area) it was 1.5. The average bund length per hectare of command area was 5.1 m in large tanks and 21.9 m in small tanks, with an average of 10.6 m for all tanks. The storage capacity (in terms of depth) of water per unit of command area averaged 1.4 m. In the traditional small reservoir three to five times more than the water requirements was supplied to the rice crop. Very low water use efficiency, which ranged between 15 and 30 kg/cm/ha of water, was found. The water use efficiency of the overall system was still lower, in the range of 11 to 21 kg/cm/ha of water, owing to heavy seepage and evaporation losses. The study of von Oppen and Subba Rao (1987) indicated that the traditional tank irrigation system is highly subsidized by the local government. It is estimated that about 97% of the cost of tank irrigation is being subsidized. Also, the farmers are benefiting greatly from the traditional tank irrigation system. Tank irrigation generally generates higher profit in alfisols than in vertisols. The value of tank command land is about two and a half to four times that of nearby drylands.

Various studies have shown that the efficiency of the traditional tank irrigation system in India is gradually declining owing to: (i) lack of appropriate soil conservation measures in the catchment areas, causing high soil erosion and siltation in the tank; (ii) inadequate maintenance of bunds, waste weirs and delivery channels; (iii) lack of effective water-user organizations; (iv) encroachment of farming on to the tank bed; (v) poor sluice location; (vi) temporal shift in seasonal distribution of rainfall; and (vii) increase in population densities (von Oppen and Subba Rao, 1987). These studies have also indicated the excellent scope for improving the performance of the traditional tank system through appropriate technical inputs and government policies.

Assessment of Adequate Water Availability in the Tank at Critical Crop Growth Stages

The central problem of water supply for agricultural production is that natural precipitation does not always occur at the right time and of the right magnitude. In many SAT areas, the tanks have been used to supply the much-needed water for supplemental irrigation. Since the construction of a tank is a costly affair, it is important first to assess the feasibility of water harvesting. For the success of any run-off water harvesting and supplemental irrigation system, this information is highly desirable.

Depending on the balance between the magnitude of run-off from the catchment compared with seepage and evaporation losses, water may or may not be available in the required quantities at the time it is most critically needed. For example, in a study, two tanks located on different alfisol watersheds at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India were selected to assess the prospects of run-off harvesting and water availability. The run-off and water-harvesting models (Pathak *et al.*, 1989; Kumar, 1991) were used to simulate the daily run-off, soil moisture and water availability in the tank. Based on the net water inflow or outflow estimations, daily available water in the tank was calculated. The probability of getting 40 mm water for irrigation from one of the tanks is large for the major part of the growing season. The conditional probabilities of availability of 20 and 40 mm water in the tanks for irrigation during periods of drought were also calculated for the tanks. The probabilities of the tank having 40 mm water for supplemental irrigation during drought periods in July was 68%, while in August and September the probability exceeded 91%. The conditional probabilities of having 20 mm of irrigation water during drought periods in July, August, September and October exceeded 97%. Probabilities of occurrence of drought stress at three crop growth stages, namely, growth stage 1 (GS1, sowing to panicle initiation), growth stage 2 (GS2, panicle initiation to anthesis) and growth stage 3 (GS3, grain-filling stage), were estimated (Pathak and Laryea, 1990). In addition, the probability of obtaining 40 mm of water for irrigation from tanks during the drought-stress period for each crop growth stage was also calculated. The chances of 40 mm of water being available from the tank during drought periods of GS2 and GS3 exceeded 90% compared with 68% for GS1.

On vertisols, Pathak and Laryea (1993) used the run-off and water-harvesting models for assessing the prospects of run-off water harvesting at Akola, Maharashtra, India. The water-harvesting model parameters were first calibrated for vertisols. Long-term daily rainfall, open pan evaporation was used, and the probability of getting 40, 60, 80 and 100 mm of water from the tank at different seepage rates was estimated. The probabilities of getting different amounts of water for supplemental irrigation from the tank are shown in Fig. 11.1. The probability of getting water was high for the most part of the crop growing season. However, the high probability of getting 100 mm irrigation water was limited to only 3 months, i.e. September, October and November. High run-off and low seepage losses were the main reasons for good availability of water in the tank (Fig. 11.2). The 10-year mean water outflow from the tank indicated that there is a possibility of increasing the tank size, since about 2200 m^3 run-off water overflows every year from the tank. The probability of occurrence of drought stress at various crop growth stages was estimated. The conditional probability of getting adequate water (>40 mm) for irrigation during drought periods for each crop growth stage was also found to be high (>92%). The analysis clearly indicates a good prospect of run-off water harvesting in the Akola region of Maharashtra. All this information is useful in developing the strategies for scheduling supplemental irrigation for the Akola region.

Sireesha (2003) assessed the prospects of run-off harvesting in three districts, i.e. Mahabubnagar, Nalgonda and Kurnool districts of Andhra Pradesh, India. The soils at the sites in Mahabubnagar and Nalgonda districts are alfisols, while in Kurnool the soils are vertisols. The water-harvesting model was used in simulating the daily run-off and water availability in the tank. Probabilities of getting 20, 40, 60, 80 and 100 mm of water for irrigation in the three districts are shown in Fig. 11.3. Results showed that the sites in Nalgonda and Mahabubnagar districts have higher prospects of run-off harvest-

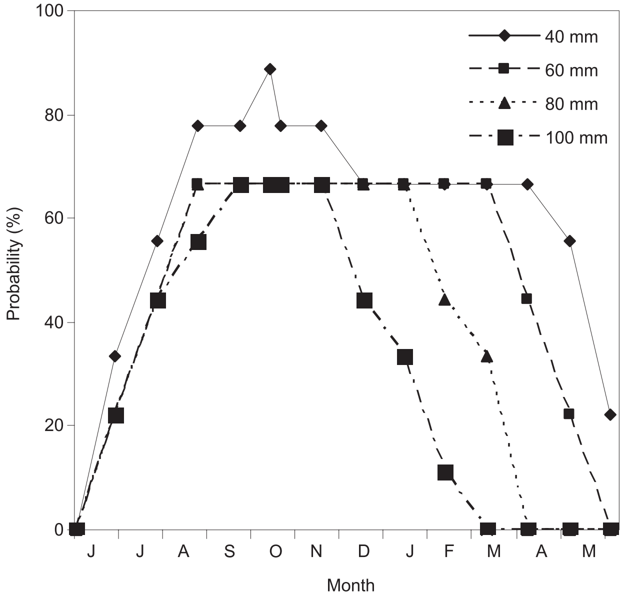


Fig. 11.1. Probabilities of obtaining 40, 60, 80 and 100 mm of water for irrigation from a tank at Akola, Maharashtra, India (based on 10 years of data).

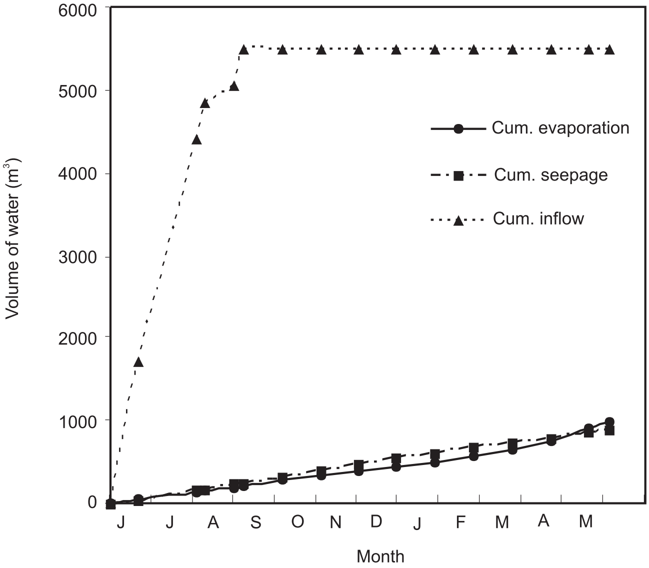


Fig. 11.2. Cumulative inflow, evaporation and seepage losses from a tank at the All India Coordinated Research Project for Dryland Agriculture (AICRPDA) Research Station, Akola, Maharashtra, India.

ing than in Kurnool district. It was found that if the seepage rate exceeds 18.0 l/m^2/day then the probability of getting an adequate amount of water (40 mm) in the tank was very low (less than 50% probability). Based on the analysis of soil samples from the three districts, the expected seepage rates should be 3–23 l/m^2/day.

Optimum Tank Size and Other Design Parameters

To determine the optimum tank size for a given catchment and crop needs is a difficult task. An excessively large tank size is expensive and may result in making the whole water-harvesting system uneconomical; on the other hand too small a tank cannot meet the irrigation demands at the critical crop stages. Also, we need to consider the expected run-off and water losses, i.e. seepage and evaporation losses from the tank. Therefore, proper sizing of the tank is very important. Several models have been developed and used for estimating the optimum tank size. Some of these models are discussed below.

Sharma and Helweg (1982) developed a methodology to optimally design and locate a small tank in a catchment. They based their computations on irrigation demand of a crop, cost of land under the tank bed, cost of irrigation, seasonal run-off expected, and other catchment descriptions such as area and length.

A simulation model combining a watershed run-off model and a maize grain-yield model was developed to determine the reservoir size necessary to ensure the availability of water on a probability basis for irrigation (Palmer *et al.*, 1982). Return period calculations were made on crop yields to obtain probability curves of yield as a function of reservoir size. It was found that the information generated by the model enabled the user to make informed decisions regarding selection and design of irrigation-water supply reservoirs.

Arnold and Stockle (1991) developed a comprehensive water management model to optimize the pond size for supplemental irrigation. The Simulation for Water Resources in Rural Basins (SWRRB) model was chosen as the basis for the simulation model. This model was modified to simulate crop yield response to supplemental irrigation. A simple economic model was also added. The model was finally linked to a sub-routine to determine the pond size that optimizes average annual return to

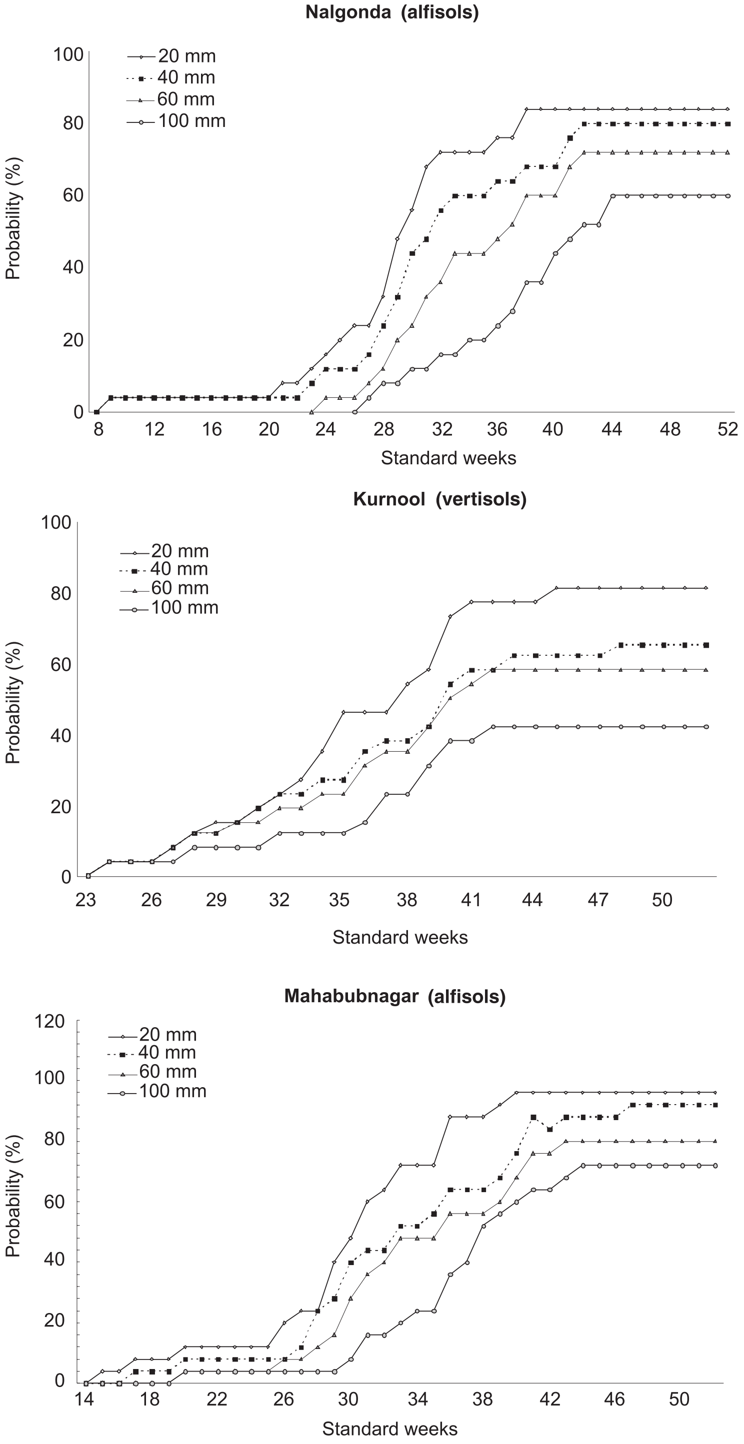


Fig. 11.3. Probabilities of obtaining 20, 40, 60 and 100 mm of water in tanks in Nalgonda, Kurnool and Mahabubnagar districts of Andhra Pradesh, India (based on 26 years of simulated data).

management. The model also develops frequency distribution for risk management. This model has been used to optimize the size of tanks in the USA and elsewhere.

Sireesha (2003) used the water-harvesting model to optimize the tank size for a given catchment and the demand for supplemental irrigation. Optimization functions were used to consider expected run-off, demand for supplemental irrigation, losses from the tank, outflow from the tank and the cost. The most cost-effective tank sizes were generally found to be not the ones with too large or too small capacities. Smaller tanks were often not able to meet even minimum supplemental irrigation requirements, while the large tanks were found to be too expensive and the returns above the optimum size were found to be very marginal.

At ICRISAT Center, 13 tanks of different designs and specifications were constructed on vertisols, vertic inceptisols and alfisols. The performance of these tanks varied considerably. The land area occupied by these tanks varied between 3 and 13% of the catchment area. The storage capacities and area under the tank ranged between 0.1 and 1.2 ha-m, and 0.2 and 0.8 ha, respectively. The storage efficiency was between 1.4 and 2.65 (Sachan and Smith, 1988). A distinctive feature of these tanks is the absence of an outlet structure. After the tank is filled, run-off is automatically diverted to the main waterway.

To achieve overall higher efficiency, the following guidelines should be adopted in the design and construction of run-off storage tanks:

- High storage efficiency (ratio of volume of water storage to excavation): the tank in a gully, depression, or on land having steep slopes. Whenever possible, use the raised inlet system to capture run-off water from upstream. This design will considerably improve the storage efficiency of the structure.
- Reduce the seepage losses: select a tank site having subsoils with low saturated hydraulic conductivity. As a rough guide, the silt and clay content of the least-conducting soil layer is inversely linked with seepage losses. Therefore, it is best to select a site having a subsoil with higher clay and silt and less coarse sand. Also, reduce the tank wetted surface area in relation to water storage volume by making a circular tank.
- Minimize the evaporation losses: as far as possible make the tanks deeper but with an acceptable storage efficiency to reduce water-surface exposure and to use a smaller land area under the tank.

Considerable information on various aspects of run-off water harvesting and supplemental irrigation could be obtained by using these models, i.e. run-off model, water-harvesting model and model for optimizing the tank size. These models can assess the prospects of run-off water harvesting and possible benefits from the irrigation. The models can also be used to estimate the optimum tank size, which is very important for the success of the water-harvesting system. The information generated can also help in developing strategies for scheduling supplemental irrigation, particularly where there is more than one drought during the cropping season (Athavale, 1986; Gunnell and Krishnamurthy, 2003).

Efficient Application of Supplemental Irrigation Water

In the SAT regions, water is a scarce resource and the amount of water available for supplemental irrigation is generally limited. In such situations, an efficient application of water is very critical as it can contribute significantly to reducing water losses and increasing water use efficiency. Broadly, the methods used for application of irrigation water can be divided into two types, namely surface irrigation systems (border, basin and furrow) and pressurized irrigation systems (sprinkler and drip).

Surface irrigation system

Currently in the SAT about 96% of the areas are irrigated using surface flood irrigation. This system is not very efficient and water losses through seepage and evaporation are very high. In the surface irrigation system, the application of irrigation water can be divided in two parts – first, the conveyance of water from its source to the field and, second, application of water in the field.

Conveyance of water to the field

In most SAT areas the water is carried to cultivated fields by open channels, which are usually unlined and therefore a large amount of water is lost through seepage. In the absence of proper lining, about 10–35% of water is lost during conveyance from the source to the field due to seepage and evaporation losses (Singh and Khan, 1999). Several lining materials, e.g. LDPE film, cement-concrete, brick masonry with plaster, slates in cement, soil:cement, soil:silt, asphaltic spray, soil:bentonite, mud plaster, saline sodic soil plaster, prefabricated clay tiles, etc., have been tried to control the seepage losses (Singh and Gupta, 1989; Singh *et al.*, 1999; Singh and Khan, 1999; Fan *et al.*, 2005). Among the materials tried, lining with saline sodic soil, clay plastering, LDPE film and soil:cement proved most promising with regard to their overall performance and the cost of lining. These materials reduced the seepage losses by 35–90% compared with the unlined channel.

On SAT vertisols, generally there is no need to line the open field channels as the seepage losses in these soils are low, mainly owing to very low saturated hydraulic conductivity (0.3–1.2 mm/h) (El-Swaify *et al.*, 1985). On alfisols and other sandy soils having more than 75% sand, the lining of open field channels or use of irrigation pipes is necessary to reduce the high seepage water losses. The use of closed conduits (plastic, rubber, metallic and cement pipes) is becoming popular, especially with farmers growing high-value crops, i.e. vegetables and horticultural crops.

Efficient field application of irrigation water

The efficient application of supplemental water in the field is probably the most important and crucial aspect of the surface irrigation system. The method of surface irrigation plays a vital role in reducing the water losses and in increasing water use efficiency. The major problem with surface flood irrigation relates to uneven distribution of applied water and associated high seepage and evaporation losses. Considerable research work has been done to improve the performance of surface irrigation on different soils and under various topographic conditions. Improved surface irrigation systems, e.g. border strip, narrow ridge and furrow, broadbed and furrow (BBF), wave-type bed and furrow, compartmental bunding, check basin, limited-irrigation dryland system (LID system) and others, were found to be suitable for different SAT region situations.

EFFICIENT APPLICATION OF SUPPLEMENTAL WATER ON SAT ALFISOLS In alfisols, with common problems of crusting, sealing and hard setting, the efficient application of supplemental water through surface irrigation is a difficult task. On these soils, surface irrigation on flat, cultivated fields results in very poor distribution of water and high water loss. At ICRISAT, Patancheru, India, experiments were conducted to find out the most appropriate land surface configuration for the application of supplemental water. The wave-shaped broadbed, with checks at every 20 m length along the furrows, was found to be most appropriate for efficient application of supplemental water and increasing crop yields (Table 11.1). It was observed that the moisture distribution across the beds was uniform in the case of wave-shaped broadbeds with checks compared with normal BBF. Sorghum yield in wave-shaped broadbeds with checks was higher at every length of run compared with normal BBF. When irrigation water was applied in the standard BBF system on alfisols, the centre of the broadbed remained dry. The centre crop row did not get sufficient irrigation water, resulting in poor crop yields. In another experiment on alfisols, the standard BBF system (150 cm) was compared with the narrow ridge and furrow system (75 cm). The

Table 11.1. Sorghum grain yield (t/ha) as affected by the water distribution in different surface irrigation systems on alfisols.

Length of furrow (m)	Normal BBF	Wave-shaped broadbeds with checks in furrows
0	2.07	2.52
20	2.38	3.91
40	2.56	4.42
60	3.06	4.54
80	3.26	4.53
100	3.08	4.42

narrow ridge and furrow system performed better than the BBF system in terms of both uniform water application and higher crop yields. The water distribution uniformity index (DU = average volume of water infiltrated in the lower one-third length/average volume of water infiltrated) was found to be higher in the narrow ridge and furrow system (0.74) compared with the standard BBF system (0.63). In the flat system, the water distribution uniformity index was in the range of 0.37 to 0.47. Also, in terms of depth of water application, outflow volume and application efficiency at the various inflow rates, the narrow ridge and furrow system performed better than the standard BBF system (Table 11.2). In the standard BBF system, the outflow volume, even at a low inflow rate of 10 l per min, was high. It was also found that the water application efficiency decreased significantly with increased inflow rates in both narrow ridge and furrow and BBF systems.

Therefore, for alfisols, the wave-shaped broadbed with checks in the furrows is the most appropriate land-surface configuration for efficient application of supplemental irrigation water, followed by the narrow ridge and furrow system. Also on these soils, low inflow rates should be used to achieve high water application efficiency and reduced outflow volumes (less than 10 l per min).

EFFICIENT APPLICATION OF SUPPLEMENTAL WATER ON SAT VERTISOLS Formation of deep and wide cracks during soil drying is a common feature of SAT vertisols. The abundance of cracks is responsible for high initial infiltration rates (as high as 100 mm/h) in dry vertisols (El-Swaify *et al.*, 1985). This specific feature of vertisols makes efficient application of limited supplemental water to the entire field a difficult task. At ICRISAT, experiments were conducted on vertisols to find out the appropriate land-surface configuration for efficient application of supplemental irrigation. Among the various systems, the BBF system was found to be most appropriate for applying irrigation water on vertisols. As compared with the narrow ridge and furrow, the BBF saved 45% of the water without affecting crop yields. Compared with narrow ridge and furrow and flat systems, the BBF system had higher water application efficiency, water distribution uniformity and better soil wetting pattern.

An important feature of the BBF system is the utility of furrows for irrigation water application. However, on SAT vertisols, a considerable amount of irrigation water applied through the furrows is often lost through the cracks present in the furrows. At the ICRISAT Center, studies conducted to evaluate the effect of shallow cultivation in furrows on the efficiency of water application showed that the rate of water advance was substantially higher in cultivated furrows as compared with that in uncultivated furrows (Fig. 11.4). Shallow cultivation in moderately cracked furrows before the application of irrigation water reduced the water required by about 27%, with no significant difference in chickpea yields (Table 11.3).

Also, the water distribution efficiency, opportunity time and depth of water application were found to be higher in the cultivated furrow treatment (Table 11.4). Therefore, for the SAT vertisols, the BBF system seems most appropriate for the efficient application of irrigation water. In case of cracks in the furrow, pre-irrigation shallow cultivation will make the BBF system more efficient in terms of both water savings and uniformity of water application.

Table 11.2. Effects of inflow rate on depth of water applied, outflow volume, and application efficiency in different landforms on alfisols.

Inflow rate (l/min)	Landform	Depth of water applied (cm)	Outflow volume (l)	Water application efficiency (%)
10	Narrow ridge and furrow	3.57	14	98.7
	BBF	3.71	226	94.2
20	Narrow ridge and furrow	4.81	1217	67.0
	BBF	3.63	3402	51.6
30	Narrow ridge and furrow	5.15	2697	48.6
	BBF	3.50	5323	39.5

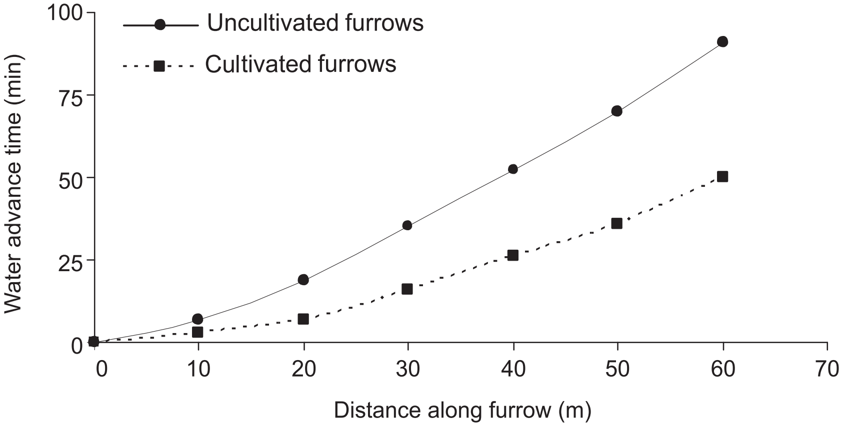


Fig. 11.4. Effect of shallow cultivation in BBF furrow on water advance on vertisols at ICRISAT Center, Patancheru, India.

Table 11.3. Grain yield of chickpea in different treatments on vertisols at ICRISAT Center, Patancheru, India[a].

Treatment	Mean depth of water application (cm)	Grain yield (kg/ha)
No supplemental irrigation	0	690
One supplemental irrigation on uncultivated furrows	6.3	920
One supplemental irrigation on cultivated furrow	4.6	912
SEM		19
CV%		5.55

[a] Source: Srivastava *et al.* (1985).

Table 11.4. Effect of pre-irrigation cultivation in the BBF furrows on opportunity time, water application and water distribution efficiency on vertisols at ICRISAT Center, Patancheru, India[a].

	Uncultivated furrows		Cultivated furrows	
Distance along the furrow length (m)	Opportunity time (min)	Depth of water application (cm)	Opportunity time (min)	Depth of water application (cm)
0	120.0	9.5	80.0	6.2
10	111.9	8.8	75.9	5.8
20	102.7	8.2	73.5	5.6
30	83.8	6.5	62.1	4.7
40	68.4	5.2	57.8	4.3
50	49.1	3.6	43.2	3.1
60	34.0	2.3	35.0	2.4
Mean water application depth (cm)		6.3		4.6
Standard deviation		2.53		1.32
Water distribution efficiency (%)		60		71

[a] Source: Srivastava *et al.* (1985).

Surge flow irrigation system

Surge flow irrigation is an efficient surface irrigation method, which enhances the water productivity by improving the efficiency of furrow irrigation. This system applies surges of water intermittently rather than in a continuous stream. These surges alternate between two sets of furrows for a fixed amount of time. The alternate wetting and 'resting' time for each surge slows down the intake rate of the wet furrow and produces a smoother and hydraulically improved surface. Thus, the next surge flows more rapidly down the wet furrow until it reaches a dry furrow. Surge irrigation provides more uniform moisture distribution and limits deep percolation losses. Surge flow does not work well on compacted soils, so it is more effective as pre-sowing irrigation and the first irrigation following cultivation. Studies at Tamil Nadu Agricultural University, Coimbatore, India have shown that surge irrigation saves 7–13% of water and increases water productivity by 19–27% (Singh, 2007). Surge flow can also save more than 35% of energy costs compared with simple furrow irrigation (Sharma and Sharma, 2007). Savings in energy and pumping costs can pay for the cost of surge irrigation valves within 2 years. This irrigation system also increases fertilizer application efficiency and lowers salt loading by reducing deep percolation. With proper planning and design this method can be extensively used to efficiently irrigate vegetable crops grown on a ridge and furrow land configuration.

Pressurized irrigation systems

The traditional surface irrigation methods (flood, border and furrow), which involve water delivery to plants through gravitation, usually result in substantial water losses and limited uniformity in moisture distribution. The improved pressurized irrigation systems enable controlled supply of water at the root zone of the crops (drip method) or aerial sprinkling in the vicinity of the plant (sprinkler method), resulting in a substantial increase in water saving and irrigation efficiency. In these systems, the required quantity of water can be applied more uniformly and precisely at the desired sites, as needed by the crop. Thus, water losses on account of deep percolation or wetting of unwanted soil volume are considerably reduced. In drip irrigation, the decreased wetted surface area results in a significant reduction in evaporation losses, which further augments saving of water. On the other hand, the favourable soil moisture regime owing to controlled application of water and soluble nutrients helps in better crop growth, enhanced yield and superior quality of produce (Singh *et al.*, 1999; Singh, 2007).

SPRINKLER IRRIGATION The sprinkler method of irrigation can be used for the efficient application of supplementary irrigation. Studies have been conducted to evaluate the conventional sprinkler system against the traditional methods of surface irrigation (border, check basin, and furrow irrigation) for various crops (Singh *et al.*, 1999). For tomato crop in sandy loam soils at Madurai, Tamil Nadu, an application of 3.5 cm water through the sprinkler method gave as much yield as a 6 cm application by the surface method, thereby saving about 34% water over 2 years (Table 11.5). For the same 6 cm irrigation level, the tomato yield in the sprinkler system was higher by 18.6% compared with the ridge and furrow system.

Recently more efficient sprinkler systems, i.e. low elevation spray application sprinkler (LESA sprinkler) and low energy precision application sprinkler (LEPA sprinkler), have been found to be extremely useful for the efficient application of irrigation water. The LESA sprinkler irrigation systems distribute water directly to the furrow at very low pressure (6–10 psi) through sprinklers positioned 30–45 cm above ground level. Conventional high-pressure impact sprinklers are positioned 1.5–2.1 m above the ground, so they are very susceptible to spray evaporation and to wind-drift, causing high water loss and uneven water distribution. The LESA systems apply water in streams rather than fine mists, to eliminate wind-drift and to reduce spray evaporation, deep percolation and underwatering. The LEPA irrigation systems further reduce evaporation by applying water in bubble patterns, or by using drag hoses or drag socks to deliver water directly to the furrow. LEPA and LESA systems concentrate water on a smaller area and increase the water application rate on the areas covered. In addition to water savings, these irrigation systems have been found to use much less

Table 11.5. Tomato yield as influenced by method and depth of irrigation at Madurai, Tamil Nadu, India, 1995–1997[a].

Method of irrigation	Depth of irrigation (cm)	Yield (t/ha) 1995	Yield (t/ha) 1996	Yield (t/ha) Mean	Water applied (cm) 1995	Water applied (cm) 1996	Water applied (cm) Mean
Sprinkler	6.7	18.39	29.55	23.97	53.6	67.5	60.6
	6.0	16.33	29.50	22.92	48.0	62.4	55.2
	4.9	13.52	27.25	20.39	39.2	54.4	46.8
	3.5	11.90	27.45	19.68	28.0	44.9	36.5
	2.2	10.22	27.65	18.94	17.6	35.8	26.7
Ridge and furrow	6.0	13.84	24.80	19.32	48.0	62.4	55.2
CD ($P = 0.05$)		1.97	3.56				

[a]Source: Singh *et al.* (1999).

energy (at least 30% less than conventional systems), which reduces fuel consumption and operational costs. Other advantages include reduced disease problems due to less wetting of foliage, and easier application of chemicals. Studies have shown that when managed properly, LEPA irrigation is 20–40% more efficient than typical impact sprinkler systems (Sharma and Sharma, 2007). While LEPA systems can be costly, this expense can be offset in 5–7 years through reduced energy savings of 35–50%, labour-cost reduction and increased crop yields.

DRIP IRRIGATION The area under drip irrigation is fast increasing in India. This is primarily due to its better performance and encouraging government policies. Drip irrigation applies small amounts of water frequently to the soil area surrounding plant roots through flexible tubing with built-in or attached emitters. Subsurface drip irrigation delivers water underground directly to roots. Since water is applied directly to individual plant roots, drip irrigation minimizes or eliminates evaporation, provides a uniform application of water to all plants, and applies chemicals more efficiently. In this irrigation system, a managed amount of water is applied, thereby avoiding deep percolation and run-off while reducing salt accumulation. Drip systems reduce farm operation and maintenance costs through energy savings and automation. Also, drip systems are the only type of irrigation that can use water efficiently on steep slopes, odd-shaped areas and problem soils.

The economics of the system in various crops were studied by evaluating productivity of different planting layouts, crop geometries and system designs to reduce the length of laterals (Sivanappan, 1997; Singh *et al.*, 1999). The results on the comparative performance of the drip system versus surface irrigation for banana are shown in Table 11.6. The application of 24 l of water per banana plant on alternate days through drip irrigation produced 31 t/ha of fruit,

Table 11.6. Banana yields as obtained by different irrigation methods and nitrogen (N) levels at Bhavanisagar, Tamil Nadu, India (average of 1994/95 and 1995/96 data).

Irrigation treatment	Yield (t/ha) at different doses of N (g per plant) 80	110	140	Mean	Water applied (cm)
Alternate day drip irrigation (l/day)					
24	30.7	30.9	31.4	31.0	96.4
32	30.8	32.2	33.2	32.1	130.4
40	30.7	31.6	33.7	32.0	161.8
Mean (drip irrigation)	30.7	31.6	32.8	31.7	129.5
Surface irrigation	27.3	28.4	29.2	28.3	193.6

which was 2.7 t/ha higher than the surface irrigation. In addition, the drip system also saved about 50% water compared with surface irrigation. In another study conducted at Parbhani (Maharashtra, India) to compare check basin irrigation, the drip irrigation increased the banana yield by 37% and saved about 32% water.

Compared with other irrigation systems, namely sprinkler and furrow irrigation, the drip systems provide the most uniform and adequate moisture to the plants (Fig. 11.5). Relative moisture varies the most in furrow irrigation, followed by sprinkler and the least in drip irrigation (Sharma and Sharma, 2007). The drip system is also most efficient in terms of water application efficiency (Table 11.7).

Although drip systems are very efficient, they do have some drawbacks. Because they may clog and are susceptible to damage by rodents, insects and sedimentation, they must be checked regularly. A good filtration system is essential for proper performance of a drip system. Hard water should be treated to discourage mineral build-up. New systems are expensive and must be designed to suit crops and local soil and climate conditions. A reliable, continuous water supply is necessary to run a drip system, and proper irrigation management and furrow shaping is necessary to prevent salt build-up. Rotating crops with different spacing requirements may be problematic after a drip system is installed. Drip irrigation may not be practical for closely spaced annual crops.

The drip irrigation is the most efficient system for the application of supplemental irrigation water. It is most effective in reducing the water losses and increasing irrigation efficiency. It is also the most economical system for high-value crops, i.e. horticultural crops and vegetables. However, the full benefits of irrigation using this system can be achieved by integrating application of fertilizers and other chemicals with irrigation water, which improves not only water use efficiency but also fertilizer use efficiency. However, its use is very limited for most of the commonly grown annual crops by resource-poor farmers in the SAT. This is primarily because of the high initial cost of the drip system, which is generally out of reach of poor farmers. Recently, a few promising low-cost drip systems, namely a gravity-fed drip system and a drip system with a low-cost filter, have been manufactured for small farmers.

Table 11.7. Efficiency of different irrigation systems[a].

Irrigation system	Range of application efficiency (%)
Drip irrigation	90–98
LEPA sprinkler	90–95
LESA sprinkler	80–90
Surge irrigation	50–70
Furrow system	40–60

[a]Source: Sharma and Sharma (2007).

Conjunctive utilization of rainfall and limited irrigation water

Stewart *et al.* (1983) developed a limited-irrigation dryland (LID) system for the efficient use of limited irrigation water for crop production. The objective of the LID system concept is to maximize the combined use of growing-season rainfall, which varies for any given year, with a limited supply of irrigation water. The unique feature of the LID system is the flexible adjustment during the crop growing season of the area of land irrigated, allowing more land to be irrigated during above-average

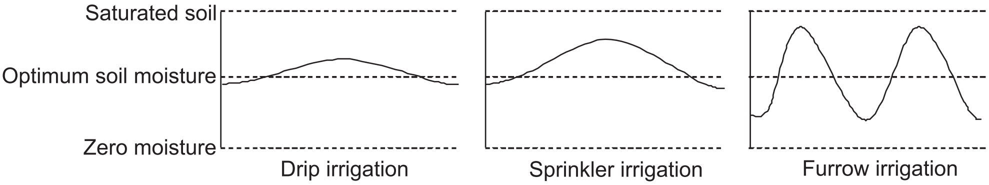


Fig. 11.5. Comparison of soil moisture in different irrigation systems (Source: Sharma and Sharma, 2007).

rainfall years than during dry or low rainfall years. Risk is low with the LID system, and the crop response is good in favourable rainfall years. This system was adopted and studied at ICRISAT Center, Patancheru, India for rainy-season sorghum on alfisols. It was found that this system is effective in increasing the water application efficiency (WAE) (Table 11.8). Results demonstrated the usefulness of the LID system in the application of limited water under uncertain and erratic rainfall conditions.

Stewart (1989) showed that, using the LID system, higher water use efficiency can be obtained for sorghum and other crops. He also mentioned that to properly use the LID system, the decision makers need to have a good understanding of the relationships of transpiration and evapotranspiration to dry matter and grain yields, and to water application rates. Unless these relationships are understood, it is difficult to make correct decisions regarding the efficient use of irrigation water. Also, these relationships must be further interpreted with regard to risk management and economics, because these factors often dictate decision making.

Crop Responses to Supplemental Irrigation

Benefits of supplemental irrigation in terms of increasing and stabilizing crop productivity have been impressive, even in the SAT areas with dependable rainfall. Excellent responses to supplemental irrigation have been reported from several locations in India (Gunnell and Krishnamurthy, 2003). For example, Singh *et al.* (1999) summarized the response of 13 crops to supplemental irrigation from 23 locations in India. The increase in grain yield over control varied from 23% in the case of sorghum to 345% in chickpea. Singh and Khan (1999) also summarized the yield responses of crops to supplemental irrigation in different locations of India; the data indicated that one supplemental irrigation at the critical stages of crop growth considerably increased the crop yields. Introduction of high-value crops such as hybrid cotton under protective irrigation further helps in enhancing the income of dryland farmers. Owing to better moisture availability through supplemental irrigation, the crops respond to the application of higher rates of nutrients. In an experiment carried out in medium deep black soils at Bijapur, Karnataka, India, the responses of horticultural crops, namely jujube (*ber*), guava and fig, to supplemental irrigation were studied. The highest (122.6%) response to supplemental irrigation was recorded in guava and the lowest (41.7%) in fig (Radder *et al.*, 1995). Vijayalakshmi (1987) reported that the effect of supplemental irrigation was largest in rainy-season sorghum and pearl millet, and yields increased by 560% and 337%; for pigeonpea the yield increased by 560%, but a comparatively lesser response was noted in groundnut, where the yield increased by only 32% (Table 11.9). For post-rainy-season crops grown at several research stations in India increase in yield by 123% for wheat, 113% for barley, 345% for safflower and 116% for rapeseed were reported. Havanagi (1982) reported similar crop yield responses to supplemental irrigation from Bangalore (India) research station.

Table 11.8. Effect of irrigation on sorghum (CSH 6) yield (kg/ha) being obtained on different sections of the slope in alfisols at ICRISAT Center, Patancheru, India, 1985–1986.

	Upper section (0–20 m)		Middle section (20–40 m)		Lower section (40–60 m)		Average yield (kg/ha)		WAE[b] (kg/mm/ha)	
Description[a]	1985	1986	1985	1986	1985	1986	1985	1986	1985	1986
Rainfed	1058	2220	1618	2110	1710	2140	1659	2150	–	–
Full irrigation	3716	3404	3516	3200	2960	3458	3390	3352	6.9	7.5
LID system	3413	3090	2600	2710	2000	2110	2671	2636	12.1	9.2

[a] Five irrigations totalling 250 mm and four irrigations totalling 130 mm were applied during 1985 and 1986, respectively, on full irrigation and LID (limited-irrigation dryland) system (upper section) treatments on an area basis.

[b] Water application efficiency (WAE) = $\frac{\text{Increase in yield due to irrigation}}{\text{Depth of irrigation}}$

Table 11.9. Effect of supplemental irrigation on crop yields at different locations in India[a].

Crops	Irrigation (cm)	Yield (t/ha)	Yield increase due to irrigation (%)	Research centre
Short-duration rainy-season crops				
Sorghum	1.6	2.51	560	Hyderabad
Maize	1	2.66	15	Jhansi
	2	4.43	40	
Finger millet	5	2.32	43	Bangalore
Soybean	8	2.05	14	Indore
Long-duration rainy-season crops				
Castor	5	1.32	31	Hyderabad
Pigeonpea	3	0.17	240	Jhansi
(sole crop)	5	0.33	560	
Tobacco	4	1.30	58	Dantiwada
Post-rainy-season crops				
Wheat	2	1.58	35	Dehra Dun
	4	2.06	78	
	6	2.60	123	
Rape seed	1	0.35	40	Ranchi
	3	0.46	84	
	5	0.54	116	

[a]Source: Vijayalakshmi (1987).

Impressive benefits have been reported from supplemental irrigation on alfisols at ICRISAT Center (El-Swaify *et al.*, 1985; Pathak and Laryea, 1990). As shown in Table 11.10, good yield responses to supplemental irrigation were obtained on alfisols in both rainy and post-rainy seasons. The average WAE for sorghum (14.9 kg/mm/ha) was more than that for pearl millet (8.8–10.2 kg/mm/ha). Intercropped pigeonpea responded less to irrigation, and the average WAE ranged from 5.3 to 6.7 kg/mm/ha for both pigeonpea/sorghum and pigeonpea/pearl millet systems. Tomatoes responded very well to water application, with an average WAE of 186.3 kg/mm/ha.

On vertisols, Srivastava *et al.* (1985) found that the average WAE was largest for chickpea (5.6 kg/mm/ha), followed by chillies (4.1 kg/

Table 11.10. Response of cropping systems to supplemental irrigation in an alfisol watershed, ICRISAT Center, Patancheru, India during 1981–1984.

Grain yield (kg/ha)[a]	Increase due to irrigation (kg/ha)	WAE[b] (kg/mm/ha)	Grain yield (kg/ha)[c]	Increase due to irrigation (kg/ha)	WAE (kg/mm/ha)	Combined WAE (kg/mm/ha)
Intercropping system						
Pearl millet			Pigeonpea			
2,353	403	10.0	1,197	423	5.3	6.8
Sorghum			Pigeonpea			
3,155	595	14.9	1,220	535	6.7	9.4
Sequential cropping system						
Pearl millet			Cowpea			
2,577	407	10.2	735	425	5.3	6.9
Pearl millet			Tomato			
2,215	350	8.8	26,250	14,900	186.3	127.1

[a]One irrigation of 40 mm; [b]WAE = water application efficiency; [c]Two irrigations of 40 mm each.

mm/ha) and safflower (2.1 kg/mm/ha) (Table 11.11). They concluded from their experiments that irrigation was profitable for sequential crops of chickpea and chillies on vertisols. The WAE was much higher on alfisols than on vertisols (Tables 11.10 and 11.11). A study was conducted at ICRISAT, Patancheru, India to evaluate the water application on early-maturing pigeonpea for a multiple-harvest system. The results showed that where water supply is limited, irrigation should be given between the main crop and the first ratoon. The yield increase due to two water applications ranged from 500 to 1000 kg/ha.

Good response to supplemental irrigation had been reported from several parts of SAT Africa (Carter and Miller, 1991; Fox and Rockström, 2000; Bennie and Hensley, 2001; Hatibu, 2003; Jenson *et al.*, 2003; Oweis and Hachum, 2003; Barron, 2004; Rockström *et al.*, 2007). On-farm research in the semi-arid locations in Kenya (Machakos district) and Burkina Faso (Ouagouya) indicates a significant scope for improving water productivity in rainfed farming through supplemental irrigation, especially if the practice is combined with soil fertility management (Barron *et al.*, 1999; Oduor, 2003). The results reported by Rockström *et al.* (2002) on yields and rainfall use efficiencies (kg grain/mm rainfall) for sorghum in Burkina Faso and maize in Kenya are shown in Fig. 11.6. Each point represents an average of five replications of water harvesting/fertilizer application treatment for a certain rainy season. In Burkina Faso, on shallow soil with low water-holding capacity, supplemental irrigation alone improved water use efficiency (WUE) (rainfall + irrigation) by 37% on average (from 0.9 to 1.2 kg/mm/ha) compared with the control (traditional rainfed practice with manure but no fertilizer). The corresponding figure for the Kenyan case, on deep soil with high water-holding capacity, was 38% (from 2.2 to 3.1 kg/mm/ha). The highest improvement in yield and WUE was achieved by combining supplemental irrigation with fertilizer application. From the experiments in the Sahel region, Fox and Rockström (2003) reported that in sorghum supplemental irrigation alone resulted in a grain yield of 712 kg/ha, while supplemental irrigation combined with fertilizer application resulted in a grain yield of 1403 kg/ha, which was higher than the farmer's normal practice by a factor of three (Table 11.12).

Barron (2004) reported from the studies made in Kenya that the water productivity for maize with supplemental irrigation was 1796 m^3/t of grain, and for maize without supplemental irrigation it was 2254 m^3/t of grain, i.e. a decrease in water productivity by 25%. The study concluded that the water-harvesting system for supplemental irrigation of maize was found to be both biophysically and economically viable. However, the viability of increased water-harvesting implementation at the catchment scale needs to be assessed so that other downstream uses of water remain uncompromised. Rockström *et al.* (2007) reported a similar response to supplemented irrigation.

From the above discussion, a large variability in crop responses to supplemental irrigation is apparent at various sites in India and elsewhere. Critically going through the results from different locations, the following key points emerge:

- The best responses to supplemental irrigation were obtained when irrigation water was applied at the critical stages of the crop. The moisture-sensitive periods differ with crop species and varieties; for example, in

Table 11.11. Response of sequential crops to supplemental irrigation in a vertisol watershed at ICRISAT Center, Patancheru, India during 1981–1985[a].

	Mean yield (kg/ha)		
Sequential cropping system	Supplementally irrigated	Increase due to irrigation	Water application efficiency (kg/mm/ha)
1. Maize + chickpea	1540	493	5.6
2. Mung + chillies	1333	325	4.1
3. Maize + safflower	1238	165	2.1

[a]Source: Srivastava *et al.* (1985).

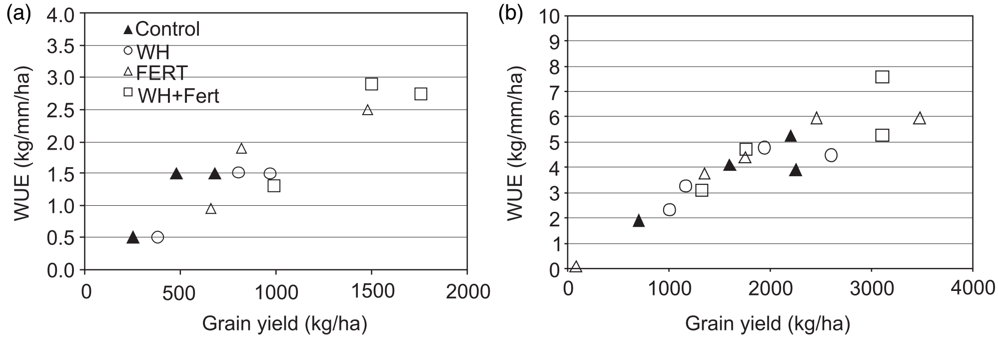


Fig. 11.6. Water use efficiency (WUE) (kg grain per unit rainfall + supplemental irrigation) for (a) sorghum in Burkina Faso, and for (b) maize in Kenya. Note: control = traditional farmers' practice with no fertilizer application; WH = supplemental irrigation using water harvesting; FERT = fertilizer application (30 kg/ha N); WH+FERT = supplemental irrigation combined with fertilizer application (Source: Rockström *et al.*, 2002).

Table 11.12. Effect of supplemental irrigation and fertilizer on sorghum grain yield (kg/ha) in Sahel during 1998–2000[a].

	1998		1999		2000		1998–2000	
Treatment[b]	Mean yield[c]	SD[d]	Mean yield[c]	SD[d]	Mean yield[c]	SD[d]	Mean yield[c]	SD[d]
TC	666 a	154	238 a	25	460 a	222	455 a	232
I	961 a	237	388 b	182	787 b	230	712 b	320
F	1470 b	254	647 c	55	807 b	176	975 c	404
IF	1747 b	215	972 d	87	1489 c	123	1403 d	367

[a] Source: Fox and Rockström (2003); [b] TC = control treatment; I = irrigation application; F = fertilizer application; IF = supplemental irrigation and fertilizer application; [c] Test of treatment effect: mean values in a column followed by different letters are significantly different at the 5% level using the Student–Newman–Keul's test; [d] SD = standard deviation.

sorghum grown in the rainy season, flowering and grain-filling stages are most critical; and in wheat, crown root initiation and grain-filling stages are most critical.

- To get the maximum benefit from supplemental irrigation, factors that limit crop productivity must be removed by using responsive cultivars and fertilizers and following other recommended practices.
- On alfisols and other sandy soils, the best results from the limited supplemental irrigation were obtained during the rainy season. On these soils, the additional benefits from one or two supplemental irrigations during the post-rainy season were found to be limited.
- On vertisols in medium- to high-rainfall areas, pre-sowing irrigation for post-rainy-season crops was found to be the most beneficial. An excellent response to pre-sowing irrigation was recorded in wheat, chickpea, safflower and linseed crops.
- On medium- to high-rainfall vertisol areas, the need for, as well as the response to, supplemental irrigation during the rainy season was not high.
- The crop responses to supplemental irrigation on lighter soils were found to be better than on heavier soils in the low- and medium-rainfall areas. However, this was not true for high-rainfall areas (<850 mm).
- To get the maximum benefit from the available water, growing high-value crops, namely vegetables and horticultural crops, is becoming popular, even with poor farmers.

Economic Evaluation of Run-off Storage Structures and Supplemental Irrigation

At ICRISAT Center, for sorghum/pigeonpea intercrop, two irrigations of 40 mm each gave an additional gross return of INRs 9750/ha. The highest additional gross return from supplemental irrigation was obtained by growing tomato (INRs 58,300/ha). These results indicate that, on alfisols, significant returns can be obtained from relatively small quantities of supplemental water. In a study conducted in vertisol watersheds at ICRISAT Center, Srivastava *et al.* (1985) found that average additional gross returns due to supplemental irrigation were about INRs 1630/ha for safflower, INRs 7900/ha for chickpea, and INRs 14,600/ha for chillies. The horticultural system with jujube (*ber*) plantation at Bijapur gave a gross income of INRs 27,962 to 37,260/ha with two to three supplemental irrigations as against INRs 23,657 to INRs 29,505/ha in control (without irrigation) (Radder *et al.*, 1995).

Singh *et al.* (1999) reported that the water harvesting and supplemental irrigation system is more economically viable with vegetables, fruits and other high-value crops. Even at 14% interest, the entire initial investment can be recovered in a period of 2–3 years. Havangi (1982) reported that crops such as chillies, tomato and cowpea responded to protective irrigation, with a benefit–cost ratio in the range of 1.4–2.5. Evaluation of farm ponds at Dehradun showed a benefit–cost ratio of 1.85–1.96, making the farm ponds a viable proposition (Singh and Khan, 1999). Radder *et al.* (1995) found the water harvesting and supplemental irrigation system economically viable at Bellary research station. Similarly, the research conducted at Bijapur revealed that an annual return of 23% on the investment was realized from the post-rainy-season sorghum or safflower grown on vertisols with two supplemental irrigations.

The economic evaluation of tank irrigation was done using a simulation model and survey of several tanks and farms from two states in India (Pandey, 1986; von Oppen and Subba Rao, 1987; Pathak and Laryea, 1990). The simulation model consisted of several component modules for rainfall, run-off, soil-water balance, yield response to irrigation and tank-water balance. Simulations were run for selected locations in India using different parameters. Studies indicated that water harvesting in central parts of India is likely to be very profitable even under high seepage rates. Taking the most common cropping system of the region, i.e. a rainy-season fallow followed by post-rainy-season wheat cropping system, Pandey (1986) found that the tanks are quite attractive for the soybean/wheat cropping pattern, even at seepage rates as high as 20 mm/day. For soybean/pigeonpea intercrop, tank irrigation is profitable at seepage rates less than 10 mm/day. At a seepage rate higher than 10 mm/day, the water-harvesting and supplemental irrigation system was not found to be economical for the soybean/pigeonpea system. Von Oppen and Subba Rao (1987) assessed the economic performance of irrigation tanks in SAT India. It was found that the spatial distribution of tank irrigation is determined primarily by physical conditions, such as hard rock substratum, total and post-monsoon rainfall, and low soil moisture-holding capacity. The study also indicated that tanks generally generate higher profits in lighter soils than in heavier soils.

Several studies in Africa have shown that supplemental irrigation systems are affordable and appropriate for single household or small community investments (Rockström *et al.*, 2007). A benefit–cost study on supplemental irrigation of maize–tomato cropping systems in Burkina Faso and Kenya found net profits of US$73 and US$390/ha annually, compared with net income losses of US$165 and US$221 in traditional systems. Moreover, the study found a strong mutual dependence between investments in supplemental irrigation and fertilizers. Studies of supplemental irrigation of maize and cabbage using farm ponds in Kenya (Ngigi *et al.*, 2005) concluded that supplemental irrigation was an economically viable option for improving livelihoods of smallholder farmers. Fox and Rockström (2000) did a benefit–cost estimate for the system with storage and use of supplemental irrigation for maize production at the Mwala field site in Kenya. The results showed that current farming systems are not sufficient to meet average household food demand for the conditions prevailing at the site. Depending on how labour cost was estimated, the structure and system of supplemental irrigation and fertilizer were estimated to provide household food self-sufficiency and net income after 1–7 years. The most profitable estimate was for no labour cost and thin plastic sheeting as a sealant. In the overall assessment, Barron (2004) found that the water-harvesting system for supplemental irrigation of maize was both biophysically and economically viable. However, the adoption by farmers depends on other factors, including investment capacity, know-how, and policy and legislative possibilities. The viability of increased water-harvesting implementation at a catchment scale needs to be assessed so that other downstream uses of water are not compromised.

Watershed-based Water Harvesting, Groundwater Recharging and Efficient Water Utilization

Upgrading rainfed agriculture is key for increasing agricultural productivity and improving livelihoods of farmers. In SAT, supplemental irrigation is of critical importance, particularly in reducing the risk associated with the dry spells. However, to maximize the benefits from the water, a more integrated approach is needed. Also in rainfed agriculture, where water is a highly variable production factor, risk reduction through integrated water management is a key to unlocking the potential of managing crops, soil fertility and pests, and allowing for diversification. For rainfed agriculture, the watershed provides a logical hydrological scale for effectively managing the rainfall, run-off and groundwater. A review of 311 case studies of watershed programmes in India by ICRISAT revealed that they are 'silently' rejuvenating rainfed areas with a mean benefit–cost ratio of 2.14 and an internal rate of return of 22%. Watershed programmes have increased water availability, augmented the irrigated area and cropping intensity, and created employment opportunities (Wani *et al.*, 2003a).

Although the integrated watershed programme includes multifaceted activities, water harvesting, groundwater recharging and its efficient utilization have been the key components of most watershed programmes in India and other Asian countries. Results from some key watershed programmes with reference to these aspects are discussed.

ICRISAT, in partnership with the National Agricultural Research Systems (NARS) in Asia, has developed an innovative and upscalable consortium model for managing watersheds holistically (Wani *et al.*, 2003b). The approach uses rainwater management as an entry-point activity, starting with *in-situ* conservation of rainwater, harvesting and groundwater recharging the excess run-off, and converging the benefits of stored rainwater into increased productivity by using improved crops, cultivars, suitable nutrient and pest management practices, and land and water management practices. The consortium strategy brings together institutions from the scientific, non-government, government, and farmers' groups for knowledge management. Convergence allows integration and negotiation of ideas among actors. Cooperation enjoins all stakeholders to harness the power of collective actions. Capacity building engages in empowerment for sustainability. This approach of integrated and participatory watershed development and management has emerged as the cornerstone of rural development in the semi-arid tropics. It ties together the biophysical notion of a watershed as a hydrological unit with the social aspect of community and its institutions for sustainable management of land, water and other resources.

At ICRISAT benchmark watersheds in India, Thailand, Vietnam and China, community- and farmer-based soil and water conservation interventions, such as check-dams, gabions and gully control structures, field bunding and percolation pits, were undertaken to improve the surface and groundwater availability. Findings in most of the watershed sites revealed that open wells located near water-harvesting structures (WHS) have significantly higher water levels compared with those away from WHS (Fig. 11.7). Also the increased availability of water in wells encouraged farmers to invest more to acquire improved irrigation facilities (Table 11.13). In Tad Fa and Wang Chai watersheds in north-east Thailand, a 45% increase in farm incomes was observed within 3 years of the watershed project. Farmers earned an average net income of US$1195 per cropping season. In Thanh Ha watershed, Vietnam, collective pumping of well water and establishing an efficient water-distribution system enabled the farmers' group to earn more

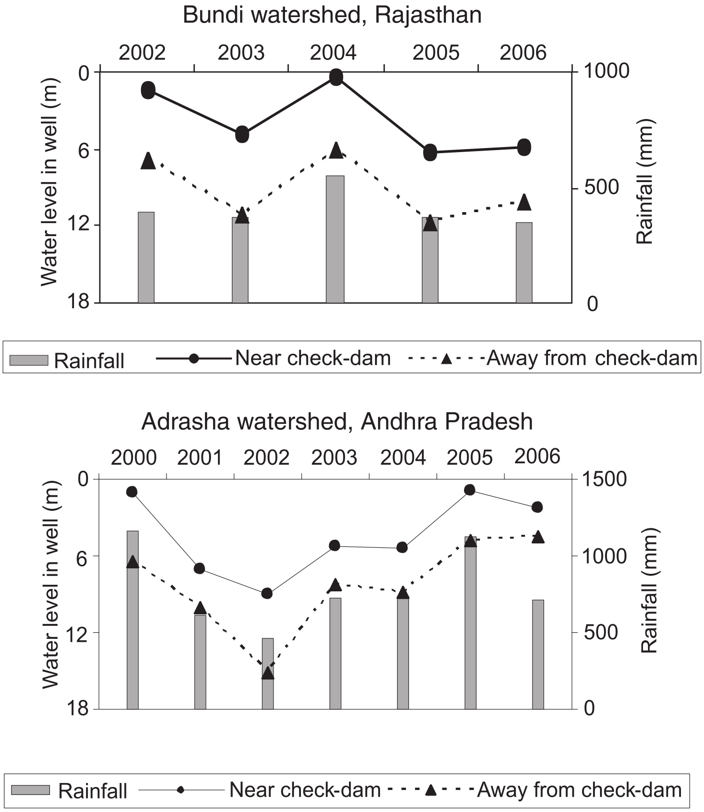


Fig. 11.7. The impact of watershed interventions on groundwater levels at two benchmark sites in India.

Table 11.13. Effect of watershed programme on irrigation equipment at the Gokulpura–Goverdhanpura watershed, Bundi, Rajasthan, India[a].

	Before watershed interventions		After watershed interventions	
Irrigation equipment[b]	Number of equipment	Number of families	Number of equipment	Number of families
Chadas (traditional method)	164	221	110	151
Diesel pumps	79	145	139	202
Electric pumps	8	18	11	18
Pipeline length (m)	1685	50	5982	82

[a]Source: Pathak *et al.* (2007); [b]Some equipment was jointly owned by the families.

income by growing watermelon, with reduced drudgery for women, who had to carry water on their heads from a long distance. Pumping of water from the river as a means to irrigate watermelon has provided maximum income for households. Improved water availability in the watershed not only resulted in increased crop productivity but a significant shift in area under cultivation took place towards high-value cereals, cash crops, vegetables, flowers and fruits.

At Fakot in Tehri Garhwal district, India, a 370 ha watershed was treated with various water-harvesting and soil conservation measures. Consequently, paddy and wheat yields increased by 1.65 t/ha and 1.93 t/ha, respectively. These measures considerably reduced run-off and soil loss from 42.0 to 0.7% and 11.0 to 2.7 t/ha, respectively. The B:C ratio, considering 25 years' project life, has been worked out as 2.71 at 12% discount rate (Sharda and Juyal, 2007).

At Salaiyur watershed in Coimbatore district, India, a total of 266 ha-cm additional rainwater storage capacity was created by rejuvenation of existing ponds and construction of new check-dams and percolation ponds on community and private lands through involvement of the watershed committee (Sikka *et al.*, 2004). This helped in augmenting groundwater recharge and improving availability of water in the wells through recuperation, which ultimately resulted in increased area under irrigation and crop diversification with high-value crops.

At Kokriguda watershed, Koraput district, Orissa, India, various soil and water conservation measures were implemented to improve water availability and control soil erosion. A water users' association was constituted to maintain the various structures. Open wells registered a water table rise of 0.32 m and crop yields increased by 15% in finger millet to 38% in upland paddy. Owing to these interventions, the area under remunerative crops like vegetables increased from 2 to 35 ha, conveyance efficiency from 23 to 95% and overall irrigation efficiency from 20 to 43% (Patnaik *et al.*, 2004).

In the Rajiv Gandhi watershed programme in Madhya Pradesh, India, over 0.7 million WHS were constructed. The programme ran on a mission mode and had over 19% people's contribution in monetary terms. There has been a 59% increase in irrigated area and a 34% decrease in wasteland area where the mission has worked. The agricultural production in the project villages increased by 37% during the rainy season and by 30% during the post-rainy season. Over 3000 villages have reported accretion in groundwater.

The above results from the integrated watershed programmes clearly indicate the excellent opportunities of implementing water harvesting, groundwater recharging and supplemental irrigation at a watershed scale. The key advantage of this approach is that these interventions can be implemented both at farmers' field level as well as community level. Also the watershed-based community organizations and institutions assist in sustainable management of WHS.

Summary and Conclusions

The SAT regions are facing multifaceted problems of water shortage, land degradation, severe poverty and escalating population pressure. Clearly there is an imbalance between natural resources, population and basic human needs in the SAT regions. If agricultural production and livelihoods are to be improved and sustained the limited rainwater available to agriculture has to be used more efficiently for increasing productivity. This can be achieved only by upgrading the current low-input rainfed agriculture. However, upgrading rainfed agriculture will require substantial investments, which is difficult unless the risk associated with drought is reduced substantially. Water harvesting and supplemental irrigation can play a critical role in reducing the risk associated with drought. This implies that the investments in water management can be used as an entry point to unlock the potential of SAT agriculture. Research work from Asia and sub-Saharan Africa clearly shows that run-off harvesting is feasible and is a profitable practice in most areas. Considerable research information in the field exists. The available information is sufficient for many regions for developing sustainable water-harvesting and supplemental irrigation systems. The greatest challenge is to use the existing knowledge in the planning and execution of a water-harvesting and supplemental irrigation system.

The efficiency of traditional tank irrigation in SAT India is gradually declining. The total area under tank irrigation is declining due to low efficiency in storage and conveyance, and poor maintenance primarily due to social and organizational problems. There is excellent scope and urgent need of improving this traditional tank system for irrigating rainfed systems.

The first important aspect of water harvesting is to assess its feasibility. Considerable information on various aspects of run-off water harvesting and supplemental irrigation could be obtained by using available models, i.e. run-off model, water-harvesting model and model for optimizing of tank size. These models can assess the prospects of run-off water harvesting and possible benefits from irrigation. These models can be also used to estimate the optimum tank size, which is extremely important for economic viability of the water-harvesting system. The information generated can also help in developing the strategies for scheduling supplemental irrigation. However, some of these models may require calibration before they can be used. The availability of appropriate data for model calibration could be a limiting factor in some SAT areas.

Efficient application of supplemental irrigation water is extremely crucial. In the past this aspect has been neglected. Currently major water losses (>40%) and poor uniformity in water distribution are occurring due to inappropriate surface irrigation methods. Using the current knowledge, considerable improvement in the performance of surface irrigation methods is possible. For SAT alfisols, the wave-shaped broadbed with checks in furrows is the most appropriate land-surface configuration for efficient application of supplemental irrigation water, followed by the narrow ridge and furrow system. For SAT vertisols, the standard BBF system is most appropriate for the application of irrigation water. In the presence of cracks in the furrows, shallow cultivation before irrigation is recommended for reducing water losses and improving uniformity of water application. The improved surge flow irrigation method can also be used for improving the performance of furrow irrigation. This system saves water, uses less energy and improves water productivity. With proper planning and design, the surge flow system can be extensively used for efficiently irrigating high-value crops grown on the ridge and furrow landform. The modern irrigation methods, namely sprinklers and drip irrigation, can play vital roles in improving water productivity. These irrigation systems are highly efficient in water application and have opened up opportunities to cultivate light-textured soils with very low water-holding capacity and in irrigating undulating farmlands. The technology has also enabled regions facing limited water supplies to shift from low-value crops with high water requirements, such as cereals, to high-value crops with moderate water requirements, such as fruits and vegetables. Implementation of these improved irrigation techniques can be used to save water and energy, and increase crop yields. However, currently the use of these improved irrigation methods is limited, primarily due to the high initial cost. Favourable government policies and the availability of credit are essential for popularization of these irrigation methods.

Impressive benefits have been reported from supplemental irrigation in terms of both increasing and stabilizing crop productivity from many parts of SAT Asia and Africa. The best response to supplemental irrigation was obtained when water was applied at the critical stages of crops. Even small amounts of water applied (10–15 mm) at critical growth stages were highly beneficial. To get the maximum benefits from supplemental irrigation other improved inputs, e.g. responsive cultivars, fertilizers, etc., must be used. On low water-holding-capacity soils, the best response from irrigation was obtained during the rainy season. On such soils, the benefits from one or two irrigations during the post-rainy season were found to be limited. On the other hand, on high moisture-holding-capacity soils, the supplemental irrigation responses during the rainy season were not very attractive. On these soils, pre-sowing irrigation for post-rainy-season crops was highly beneficial.

The water harvesting and supplemental irrigation systems were found to be economically viable for most SAT crops. Higher benefits were recorded with vegetables, fruits and other high-value crops. The economic viability of the water-harvesting systems was found to be highly linked with the seepage rates. At high seepage rates the system was not economically viable for low-value crops. In SAT Africa, the economic viability of supplemental irrigation was linked to the application of fertilizers and other improved practices.

Finally, there is a need to have a new paradigm for water management in the SAT areas, where at watershed scale water needs to be managed in an integrated manner from rainfed to supplemental irrigation using harvested runoff water or recharged groundwater. Evidence from various integrated watershed projects in India clearly shows the excellent scope of runoff water harvesting, groundwater recharging and efficient utilization at the watershed scale. This approach provides greater opportunity for improving water availability for supplemental irrigation and sustaining the water-storage structures through community participation and institutional support.

References

Arnold, J.G. and Stockle, C. (1991) Simulation of supplemental irrigation from on-farm ponds. *Journal of Irrigation and Drainage Engineering* 117(3), 408–424.

Athavale, R.N. (1986) Hydrological basis of a strategy for scheduling supplementary irrigation to cereal crops in dryland agriculture. In: Kanwar, J.S. (ed.) *Proceedings of Symposium of National Seminar on Water Management – the Key to Developing Agriculture*, 28–30 April 1986, National Science Academy, New Delhi, India. Agricole Publishing Academy, New Delhi, India, pp. 250–275.

Barron, J. (2004) Dry spell mitigation to upgrade semi-arid rainfed agriculture: water harvesting and soil nutrient management. PhD thesis, Natural Resources Management, Department of Systems Ecology, Stockholm University, Stockholm, Sweden.

Barron, J., Rockström, J. and Gichuki, F. (1999) Rainwater management for dry spell mitigation in semi-arid Kenya. *East African Agriculture and Forestry Journal* 65(1), 57–69.

Bennie, A.T.P. and Hensley, M. (2001) Maximizing precipitation utilization in dryland agriculture in South Africa – a review. *Journal of Hydrology* 241, 124–139.

Carter, D.C. and Miller, S. (1991) Three years with an on-farm macro-catchment water harvesting system in Botswana. *Agricultural Water Management* 19, 191–203.

El-Swaify, S.A., Pathak, P., Rego, T.J. and Singh, S. (1985) Soil management for optimized productivity under rainfed conditions in the semi-arid tropics. *Advances in Soil Science* 1, 1–64.

Fan, T., Stewart, B.A., Payne, W.A., Wang, Y., Song, S., Luo, L. and Robinson, C.A. (2005) Supplemental irrigation and water–yield relationships for plasticulture crops in the loess plateau of China. *Agronomy Journal* 97, 177–188.

FAO (Food and Agriculture Organization of the United Nations) (2002) *World Agriculture: Towards 2015/2030: Summary Report*. FAO, Rome, Italy.

Fox, P. and Rockström, J. (2000) Water harvesting for supplemental irrigation of cereal crops to overcome intra-seasonal dry-spells in the Sahel. *Physics and Chemistry of the Earth, Part B Hydrology, Oceans and Atmosphere* 25(3), 289–296.

Fox, P. and Rockström, J. (2003) Supplemental irrigation for dry-spell mitigation of rainfed agriculture in the Sahel. *Agricultural Water Management* 61(1), 29–50.

Gunnell, Y. and Krishnamurthy, A. (2003) Past and present status of run-off harvesting systems in dryland peninsular India: a critical review. *Ambio* 32(4), 320–323.

Hatibu, N. (2003) Rainwater management: strategies for improving water availability and productivity in semi-arid and arid areas. In: *Issues of Water Management in Agriculture: Compilation of Essays, Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka. http://www.iwmi.org/assessment%20

Havanagi, G.V. (1982) Water harvesting and life saving irrigation for increasing crop production areas of Karnataka. In: *Proceedings of the Symposium on Rainwater and Dryland Agriculture.* Indian National Science Academy (INSA), New Delhi, India, pp. 159–170.

Jenson, J.R., Bernhard, R.H., Hansen, S., McDonagh, J., Moberg, J.P., Nielsen, N.E. and Nordbo, E. (2003) Productivity in maize based cropping systems under various soil-water-nutrient management strategies in a semi-arid, Alfisol environment in East Africa. *Agricultural Water Management* 59, 217–237.

Kumar, A. (1991) Modeling run-off storage for small watersheds. MTech thesis, Asian Institute of Technology, Bangkok, Thailand.

Ngigi, S.N, Savenije, H.H.G., Thome, J.N., Rockström, J. and Penning de Vries, F.W.T. (2005) Agro-hydrological evaluation of on-farm rainwater storage systems for supplementary irrigation in Laikipia district of Kenya. *Agricultural Water Management* 73(1), 21–41.

Oduor, A. (2003) Hydrological assessment of run-off catchment schemes: a case of water harvesting using underground innovative tanks for supplementary irrigation in semi-arid Kenya. MSc thesis. WERM 03,04, UNESCO–IHE, Delft, the Netherlands.

Oweis, T. and Hachum, A. (2003) Improving water productivity in dry areas of West Asia and North Africa. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement.* CAB International, Wallingford, UK, pp. 179–198.

Palmer, W.L., Barfield, B.J. and Haon, C.T. (1982) Sizing farm reservoirs for supplemental irrigation of corn. Part I: modelling reservoir size yield relationship. *Transactions of American Society of Agricultural Engineers* 25, 372–376.

Pandey, S. (1986) Economics of water harvesting and supplementary irrigation in the semi-arid tropics of India: a systems approach. PhD thesis, University of New England, Australia.

Pathak, P. and Laryea, K.B. (1990) Prospects of water harvesting and its utilization for agriculture in the semi-arid tropics. In: *Proceedings of Symposium of the SADCC (Southern African Development Coordination Conference), 8–10 October 1990*. Land and Water Management Research Program, Gaborone, Botswana, pp. 266–278.

Pathak, P. and Laryea, K.B. (1993) Runoff water harvesting and supplemental irrigation in SAT. In: *Resource Management Program Annual Report*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 56–58.

Pathak, P., Laryea, K.B. and Sudi, R. (1989) A run-off model for small watersheds in the semi-arid tropics. *Transactions of American Society of Agricultural Engineers* 32, 1619–1624.

Pathak, P., Wani, S.P., Sudi, R., Chourasia, A.K., Singh, S.N. and Kesava Rao, A.V.R. (2007) Rural prosperity through integrated watershed management: a case study of Gokulpura-Goverdhanapura in Eastern Rajasthan. *Global Theme on Agroecosystems Report No. 36*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Patnaik, U.S., Choudary, P.R., Sudhishri, S., Dass, A. and Paikaray, N.K. (2004) *Participatory Watershed Management for Sustainable Development in Kokriguda watershed, Koraput, Orissa*. CSWCRTI, Research Centre, Sunabeda, India.

Radder, G.D., Itnal, C.J. and Belgaumi, M.I. (1995) Protective irrigation (life saving) – principles and practices. In: Singh, R.P. (ed.) *Sustainable Development of Dryland Agriculture in India*. Scientific Publishers, Jodhpur, India.

Rockström, J., Barron, J. and Fox, P. (2002) Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Physics and Chemistry of the Earth* 27, 949–959.

Rockström, J., Hatibu, N., Oweis, T.Y. and Wani, S.P. (2007) Managing water in agriculture. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–352.

Sachan, R.C. and Smith, G.D. (1988) Runoff collection and use in rainfed agriculture – the ICRISAT experience. Consultation on Supplementary Irrigation, Rabat (Morocco), 7–9 December 1987. Food and Agriculture Organization of the United Nations, Rome, Italy, pp. 27–40.

Sharda, V.N. and Juyal, G.P. (2007) Rainwater harvesting, groundwater recharge and efficient use in high rainfall areas. In: *Ensuring Water and Environment for Prosperity and Posterity Souvenir*. 10th Inter-Regional Conference on Water and Environment (ENVIROWAT 2007), 17–20 October 2007, organized by Indian Society of Water Management in collaboration with Indian Society of Agricultural Engineers and International Commission on Agricultural Engineering, pp. 59–70.

Sharma, K.D. and Sharma, A. (2007) Strategies for optimization of groundwater use for irrigation. In: *Ensuring Water and Environment for Prosperity and Posterity Souvenir*. 10th Inter-Regional Conference on Water and Environment (ENVIROWAT 2007), 17–20 October 2007, organized by Indian Society of Water Management in collaboration with Indian Society of Agricultural Engineers and International Commission on Agricultural Engineering, pp. 52–58.

Sharma, P.N. and Helweg, O.J. (1982) Optimal design of a small reservoir system. *ASCE Journal of Irrigation and Drainage* IR4, 250–264.

Sikka, A.K., Madhu, M., Chand, S., Selvi, V., Singh, D.V., Sundarambal, P. and Jeevarathnam, K. (2004) *Participatory Watershed Management for Sustainable Development in Salaiyur Watershed, Coimbatore, Tamil Nadu*. CSWCRTI, Research Centre, Udhagamandalam, India.

Singh, H.P. (2007) Enhancing water productivity in horticultural crops. In: *Ensuring Water and Environment for Prosperity and Posterity Souvenir*. 10th Inter-Regional Conference on Water and Environment (ENVIROWAT 2007), 17–20 October 2007, organized by Indian Society of Water Management in collaboration with Indian Society of Agricultural Engineers and International Commission on Agricultural Engineering, pp. 40–48.

Singh, H.P. and Gupta, J.P. (1989) Scope of water harvesting and control of water losses in deep percolation. In: *International Symposium on Managing Sandy Soils*, 6–10 February 1989, Central Arid Zone Research Institute (CAZRI), Jodhpur, India.

Singh, R.P. and Khan, M.A. (1999) Rainwater management: water harvesting and its efficient utilization. In: Singh, H.P., Ramakrishna, Y.S. and Venkateswaralu, B. (eds) *Fifty Years of Dryland Agricultural Research In India*. Central Research Institute for Dryland Agriculture (CRIDA), Hyderabad, India, pp. 301–313.

Singh, S.R., Chaudhary, T.N., Bhatta, R.K., Bhatnagar, P.R., Saha, B. and Patil, N.G. (1999) Irrigation water management. In: Singh, G.B. and Sharma, B.R. (eds) *Fifty Years of Natural Resource Management Research in India*. Central Soil Salinity Research Institute (CSSRI), Karnal, India, pp. 40–48.

Sireesha, P. (2003) Prospects of water harvesting in three districts of Andhra Pradesh. MTech thesis, Centre for Water Resources, Jawaharlal Nehru Technological University (JNTU), Hyderabad, India.

Sivanappan, R.K. (1997) State of the art in the area of water harvesting in semi arid parts of the world. Presented at the Workshop on Water Harvesting for Supplementary Irrigation of Staple Food Crops in Rainfed Agriculture, Stockholm University, Stockholm, Sweden.

SIWI (2000) *Water Harvesting for Upgrading of Rainfed Agriculture: Problem Analysis and Research Needs*. Persson, G. (ed.), SIWI, Stockholm, Sweden.

Srivastava, K.L., Pathak, P., Kanwar, J.S. and Singh, R.P. (1985) Watershed-based soil and rain water management with special reference to Vertisols and Alfisols. Presented at the National Seminar on Soil Conservation and Watershed Management, 5–7 September 1985, New Delhi, India.

Stewart, B.A. (1989) Limited-irrigation/dryland farming systems for efficient water management in semi-arid environments. In: *Management of Vertisols for Improved Agricultural Production: Proceedings of an IBSRAM Inaugural Workshop, 18–22 February 1985*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp.101–112.

Stewart, B.A., Musick, J.T. and Dusek, D.A. (1983) Yield and water use efficiency of grain sorghum in a limited irrigation–dryland system. *Agronomy Journal* 75, 629–634.

Troll, C. (1965) Seasonal climates of the Earth. In: Rodenwaldt, E. and Jusatz, H. (eds) *World Maps of Climatology*. Springer-Verlag, Berlin.

Vijayalakshmi, K. (1987) Soil management for increasing productivity in semi-arid red soils: physical aspects. In: Pathak, P., El-Swaify, S.A. and Singh Sardar (eds) *Proceedings of the Consultant's Workshop on the State of the Art and Management Alternatives for Optimizing the Productivity of SAT Alfisols and Related Soils,* 1–3 December 1983. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 109–115.

von Oppen, M. and Subba Rao, K.V. (1987) Tank irrigation in semi-arid tropical India – economic evaluation and alternatives for improvement. Research Bulletin No. 10. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003a) Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In: Kijne, W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 199–215.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003b) Farmer-participatory integrated watershed management: Adarsha watershed, Kothapally, India – an innovative and upscalable approach. Case 7. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council and Centre Directors Committee on Integrated Natural Resources Management, Consultative Group on International Agricultural Research (CGIAR), Washington, DC, USA; and Food and Agriculture Organization of the United Nations (FAO), Rome, Italy, pp. 123–147.

12 Integrated Farm Management Practices and Upscaling the Impact for Increased Productivity of Rainfed Systems

T.K. Sreedevi* and S.P. Wani**

International Crops Research Institute for the Semi-Arid Tropics (ICRISAT),
Patancheru 502 324, Andhra Pradesh, India;
*emails: *t.sreedevi@cgiar.org; **s.wani@cgiar.org*

Introduction

Most countries in the world depend primarily on rainfed agriculture for their food grains. Despite large strides made in improving productivity and environmental conditions in many developing countries, more than 850 million poor people in Africa and Asia still face poverty, hunger, food insecurity and malnutrition, where rainfed agriculture is the main agricultural activity. Although the importance of rainfed agriculture varies regionally, it produces most food for poor communities in developing countries (Rockström *et al.*, 2007; also see Chapter 1, this volume). These problems are exacerbated by adverse biophysical growing conditions and the poor socio-economic infrastructure in many areas in the semi-arid tropics (SAT). The SAT is home to 38% of the developing countries' poor, 75% of whom live in rural areas. Over 45% of the world's hungry and more than 70% of its malnourished children live in the SAT.

The challenges of outscaling in investments and policies

In a recent Comprehensive Assessment of Water for Food and Water for Life, a detailed review of managing water in rainfed agriculture listed the challenges of outscaling in investments and policies (Rockström *et al.*, 2007). Investments in agricultural research in savannah agroecosystems in the past have generated highly disappointing results (Seckler and Amarasinghe, 2004). A reason for this is the lack of focus on water resource management in rainfed agriculture. Instead, the focus at farm level since the late 1950s has mainly been on crop research and soil conservation and partly on *in-situ* water conservation (maximizing rainfall infiltration), through various strategies of terracing, bunding and ridging. Management of water resources has been conducted on a larger scale oriented towards blue water flows in irrigated agriculture. It is only in the past 10–15 years that science and technology development has focused more strongly on water management in rainfed agriculture (on water harvesting and supplemental irrigation in rainfed systems), and on tillage research focused in more explicit terms on water conservation (conservation tillage systems) at the farm scale (Rockström *et al.*, 2007).

Failure of outscaling innovation – indigenous and external

Upgrading rainfed agriculture requires that technologies (indigenous or improved) are strongly

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

adapted to local biophysical and sociocultural conditions accompanied by institutional and behavioural changes (Harris *et al*., 1991; van Duivenbooden *et al*., 2000). As experienced by several researchers, it is quite difficult to assess the impact of various natural resource management (NRM) interventions simply by adopting normal econometric methods used for assessing the impact of commodity-based interventions (Shiferaw *et al*., 2004).

Well-established evidence points to the important role of social and ecological crises in the adoption of new thinking and system transformation. Adoption of conservation agriculture in several parts of the world was driven by crises, e.g. in the USA as a response to the Dust Bowl in the 1930s, in part of Latin America as a response to an agrarian yield crisis, and in Zambia as a response to droughts. Increased emphasis on watershed management in India is largely to cope with droughts in drought-prone areas, i.e. drylands in India after severe droughts in the early 1980s. Established but incomplete evidence from the Sahel suggests that recent widespread adoption of soil and water management practices in Niger and Burkina Faso forms part of a response to crises related to land degradation and possibly climate change.

Moreover, investments in rainfed agriculture pose serious challenges as large numbers of households are small with marginal farmers. Furthermore, most rainfed areas have poor infrastructure facilities as large investments have been laid out in high-potential irrigated areas for a long time. Integrated watershed management approaches have shown the potential for scaling-out benefits, ensuring community participation largely due to tangible economic benefits as well as capacity development through knowledge sharing (Wani *et al*., 2000; 2003d).

In rainfed areas the challenges are many, along with the widespread limitations of the capacity of local institutions engaged in agricultural development and extension to promote management of rainwater. This is a knowledge-intensive extension effort, which suffers from limited information of the options available, social and economic constraints to adoption, lack of enabling environments and backup services, poor market linkages, weak infrastructure and low means to pay.

Previous focus on blue water has generated weak policies for water investments in rainfed agriculture

The Comprehensive Assessment of Water for Food and Water for Life has recommended discarding the artificial divide between irrigated and dryland agriculture as there is a continuum from fully rainfed to fully irrigated agriculture (Molden *et al*., 2007). However, traditionally the obsolete distinction between rainfed and irrigated agriculture translates to a wider approach to water resource management, focusing on management of rainfall. A result of the historic blue water (run-off) focus in agricultural policy is a history of weak water governance and policies for rainfed agricultural development. Water resource management for agriculture is normally governed under ministries for water affairs, and focuses entirely on developing and allocating water for large-scale irrigation, drinking water and hydropower. This has resulted in a downstream focus, with upper catchment areas, where rainfed agriculture predominantly is practised, being seen primarily as run-off- or blue-water-generating zones. Ministries of agriculture have focused on the ‘dry’ parts of agricultural development, and the tendency in the past was to give highest priority to erosion control rather than water management in general. Thus, although proven knowledge for better management of rainwater exists, investments in turning this knowledge into innovations in governance, policy, institutions, practices and technologies to support the smallholder farmers have been very limited.

Lately, increasing attention is being paid to management of green water (soil moisture) resources to upgrade rainfed agriculture. In the last few years, there has been an increased priority to develop policies and to build capacity in favour of investments in water management in rainfed agriculture. In several countries, central and state governments have emphasized management of rainfed agriculture under various programmes. Important efforts have, for example, been made under the watershed development programmes in India. Originally, these programmes were implemented by different ministries such as the Ministry of Agriculture, the Ministry of Rural Development, and the Ministry of Forestry and Environment, causing difficulties for integrated water management. Recently, steps were taken to unify the programme according to the 'Hariyali Guidelines' (Wani *et al.*, 2006b). In 2005, the National Commission on Farmers adopted a holistic integrated watershed management approach, with focus on rainwater harvesting and improving soil health for sustainable development of drought-prone rainfed areas (Government of India, 2005). In India, the government has established the National Rainfed Area Authority (NRAA) and it has brought out common guidelines for watershed development (Government of India, 2008). Recently the Ministry of Agriculture and the Ministry of Rural Development, who implement a large number of watershed programmes, initiated a Comprehensive Assessment of impacts of watershed programmes in India to identify strengths and weaknesses for enhancing impacts (Wani *et al.*, 2008a).

There is thus growing evidence of the importance of water investments in rainfed agriculture. Governance and management is gradually re-directed in certain regions of the world towards water management for upgrading rainfed agriculture as a key strategy for reducing poverty and increasing agricultural production. It is further increasingly clear that water management for rainfed agriculture requires a landscape perspective, and involves cross-scale interactions from farm household scale to watershed scale.

New Efforts Required to Promote Innovation and Adaptive Adoption

Upgrading rainfed agriculture involves integrated approaches to social and ecological management. A challenge facing low-productive rainfed agriculture is the need for innovations in management of water, which requires the introduction of novel technologies and management practices, e.g. water harvesting and conservation agriculture (Rockström *et al.*, 2007). A key for successful adoption and outscaling is the combination of innovation and adaptation. Adaptive co-management between local communities and knowledge-providing agents, e.g. researchers, where knowledge sharing and transformation is carried out in an iterative process, is a promising approach for successful adoption. Participatory approaches, farmer field schools and action research methods are but a few important tools for adaptive co-management.

Integrated approaches required to upgrade rainfed agriculture

An integrated approach to rainwater management is necessary, where the links are addressed between investments and risk reduction, between land, water and crop, and between rainwater management and multiple livelihood strategies. Strategies to enable upgrading including technologies and management are generally known; however, the missing links for scaling-up and scaling-out are institutions and social and economic processes which can link to suitable policies.

Important success from integrated approaches has been experienced in Asia, e.g. the integrated watershed management approach in India, where local ownership is combined with tangible economic benefits for individual rural households (Wani *et al.*, 2003d). The experience in India highlights the limitation of a compartmental approach, where the benefits from increased productivity were not realized to the desired extent, equity issues were not addressed and, moreover, community participation was not achieved, resulting in neglect of the various water-harvesting structures in the watersheds (Joshi *et al.*, 2005).

An integrated approach to land, water and crop management is required on-farm while meeting watershed and basin development strategies to increase yields in rainfed agriculture. Bright spots and successes are not directly transferable to other socio-ecological conditions but require adaptation and co-management. Benefits from rainwater in supporting all forms of biomass growth, e.g. for cultivated crops, pasture for livestock, non-cultivated food-plants, fuel and construction wood, indicate that rainwater plays an important role in determining overall resilience of rural communities practising rainfed farming systems. Thus, an integrated approach which takes into account all these aspects of water use is needed when investing specifically in upgrading rainfed agriculture.

Community watershed as a growth engine for development of dryland areas

The recent Comprehensive Assessment of watershed programmes in India undertaken by the consortium led by ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) has recommended an urgent action to improve water management and the opportunity to double the productivity of dryland small farms in rainfed areas (Wani *et al.*, 2008a). The Comprehensive Assessment of watersheds has identified the community watershed as a growth engine for development of dryland areas.

The government has moved the watershed agenda forward in various ways: (i) with constitutional amendment to enforce more responsibility on *panchayati raj* departments for rural development; (ii) by refining watershed guidelines as lessons have been absorbed; (iii) by converging the drought-prone-area programmes with rural employment guarantee and watershed programmes around unified watershed guidelines; and (iv) most recently by unifying the guidelines and establishment of the NRAA. Further, the Planning Commission has taken cognizance of the recommendations of various task force groups. There are studies of public–private sector partnerships in watershed execution. The Government of Andhra Pradesh, which accounts for 40% of the total of watersheds in the country under implementation, has adjusted watershed budgetary allocations up to 27% for livelihood activities for women and vulnerable groups; and the Government of Madhya Pradesh appointed non-governmental organizations (NGOs) as watershed-implementing agencies throughout the state. Since 2003, several countries have approached India for assistance in piloting watershed work.

The Common Features of the Watershed Development Model

Government agencies, development thinkers, donors, researchers and NGOs have gradually learnt from each other (though some are ahead of the field and others deficient in some aspect or other, principally in people participation or in the science), but generally nowadays the better models have some or all of the following features in common (Wani *et al.*, 2008c):

- Participation of villagers as individuals, as groups or as a whole, increasing their confidence, enabling their empowerment and their ability to plan for the future and for self-determination.
- Capturing the power of group action in the village, between villages and from federations, e.g. capturing economies of scale by collective marketing.
- The construction of basic infrastructure with contributions in cash or labour from the community.
- Better farming techniques, notably the improved management of soil and water, diversifying the farming system and integrating the joint management of communal areas and forest.
- The involvement of the landless, often in providing services.
- Arrangements for the provision of basic services and infrastructure.
- The establishment of village institutions and links with the outside world.
- Improved relationships between men and women.
- Employment and income generation by enterprise development in predominantly but not exclusively agricultural-related activities.

And sometimes:

- The fusion of research and development (R&D) by capturing the extraordinary power of participatory technology development, including varietal selection with direct links to germplasm collections.
- Complete avoidance of corruption so that trust is built and all the benefits pass to the community.
- Reduction in distressed migration.

Recent additions to the watershed model

- The pragmatic use of scientific knowledge as the entry point rather than money, complete dole-out by ensuring tangible economic benefit from low-cost interventions that generate rapid and substantial returns at low level of risk. Among these are novel interventions

focusing on seeds of improved cultivars, integrated pest management (IPM), micronutrients, and soil conservation and water table recharge structures.
- A broad-based approach to income generation, involving the private sector associated with scientific advances and markets: for instance, in the remediation of micronutrient deficiencies; in the marketing of medicinal and aromatic plants; with premium payments paid by industrial processors for aflatoxin-free maize and groundnut; with high-sugar sorghum, and selected crops such as *Jatropha* and *Pongamia* sold to industry for ethanol and biodiesel production; with the production for sale of commercial seed, hybrid varieties and biopesticides.
- Using new science methodologies to improve performance such as remote sensing for monitoring and feedback to farmers, yield gap analysis and rapid assessment of the fertility status of the watershed.
- Building productive partnerships and alliances in a consortium for research and technical backstopping, with the members brought together from the planning stage.
- A concern to create resilience in the watershed and its community to climate change and to events of post-programme intervention.

Where best applied, the model has led to profound farming-system changes, improved food self-sufficiency, expanded employment and commerce, and enhanced incomes. Where indifferently executed the approach has led to very little impact, as we shall see in what follows. There is indeed something here analogous to the 'yield gap' exhibited between research station and farmers' yields. Much of the difference can be captured by implementing agencies 'catching up' with best practice. The more recent linking of natural resource science with the private sector markets and with people's broader livelihoods in consultation with them is transforming the dynamic and success rate of development efforts (Wani *et al.*, 2008c).

Broad overall conclusions about watershed performance and impact

The importance of rainfed agriculture in India has been underscored by several recent studies. The watershed approach is a paradigm that works in all rainfed circumstances, has delivered important benefits and impacts, and needs to be implemented on a large scale. But watershed impact covers a spectrum from 'no better than ad hoc development schemes' to impressive improvements of the natural resource endowment and of agricultural production, and a transformation of the socio-economy.

The difference in result between indifferent and best watershed practice is analogous to the 'yield gap' in crop production. In part, this is because the watershed approach has been rapidly evolving and the Comprehensive Assessment has been looking at a field in which the goal posts have repeatedly been moved. In part, it is due to deficiencies in execution.

To consolidate and build upon the foundation already laid and universally gain the impact that is possible, the government should undertake some difficult tasks, most notably introducing a new 'mind set' or different form of approach that accepts the following (Wani *et al.*, 2008c):

- Watershed development is not just a means to increase production or to conserve soil and water but an opportunity for the fully integrated and sustained development of human and natural resources.
- The approach is valid across various rainfall regimes over vast tracts of India and can contribute in large measure to the simultaneous achievement of the government's production, environmental and social goals.
- Sustainability and better social impact and equity are very important issues with pro-poor interventions not as a spin-off or afterthought but planned and integrated with the whole.
- There are vast opportunities to reduce costs and increase output by improving the appropriateness and extent of technology.
- There is obvious value in converging government schemes in the interest of impact and sustainability, rather than a spread of activity; this is particularly important in the case of water and schemes aimed to reach the poor.

Watersheds should be seen as a business model. This calls for a shift in approach from subsidized activities to knowledge-based entry points and from subsistence to gaining tangible economic benefits for the population of the watershed at large. This is being done by productivity enhancement, diversification to high-value enterprises, income-generating activities, market links, public–private partnerships, micro-entrepreneurship and a broad-based community involvement.

Moving forward requires that a lack of capacity to effectively implement programmes is addressed. Implementing agencies need to expand and broaden their capacities and skills, while communities need to strengthen their institutions and their skills. This will require a longer implementation period of 7–8 years, with more time spent in preparation and in post-intervention support. It also requires additional funds and more flexibility in using budgets and the engagement of specialist service providers (Wani *et al*., 2008c).

One of the weakest aspects lies in the generation and dissemination of technology. A big improvement is needed in making appropriate technology and information accessible to the watershed community. The remedy lies in devising technology for the drier and wetter parts of the rainfed area, more participatory development research and in forming consortia, and employing agencies to provide specialist technical backstopping.

There is a crucial need to improve monitoring and evaluation and the feedback of the information obtained to constantly improve performance. Only a few key indicators need to be monitored in all watersheds. At one or two representative watersheds in each district, a broad range of technical and socio-economic parameters should be measured to provide a scientific benchmark and a better economic valuation of impact than is currently possible (Wani *et al*., 2008a,c).

Operationalizing the community watershed as a growth engine

Community watershed development programmes are used as growth engines for sustainable development of rainfed areas (Wani *et al*., 2003a, 2006b, 2008b; Chapter 14, this volume). However, the major challenge is scaling-up to large areas, as successful watersheds remain few and unreplicated (Kerr *et al*., 2002; Joshi *et al*., 2005). Recently ICRISAT has developed and evaluated an integrated consortium approach for sustainable development of community watersheds with technical backstopping and convergence (Wani *et al*., 2002, 2003a). Most farming problems require integrated solutions, with genetic, management-related, and socio-economic components. In essence, plant breeders, social scientists and NRM scientists must integrate their work with that of private and public sector change agents to develop flexible cropping systems that can respond to rapid changes in market opportunities and climatic conditions. The systems approach looks at various components of the rural economy – traditional food grains, new potential cash crops, livestock and fodder production, as well as socio-economic factors such as alternative sources of employment and income. The Integrated Genetic and Natural Resource Management (IGNRM) approach is participatory, with farmers closely involved in technology development, testing and dissemination. The adoption of this new paradigm in rainfed agriculture has shown that with proper management of natural resources the systems productivity can be enhanced and poverty can be reduced without causing further degradation of the natural resource base (Rockström *et al*., 2007; Wani *et al*., 2008b). The scaling-up of these innovations with technical support from the ICRISAT-led consortium has been attempted in Andhra Pradesh, India through Andhra Pradesh Rural Livelihoods Programme (APRLP) supported by the Department for International Development (DFID), UK; in Karnataka (India), Sujala watershed programme supported by the World Bank; in three districts of Madhya Pradesh and Rajasthan with support from the Sir Dorabji Tata Trust (SDTT), Mumbai, India; and four countries in Asia (India, Thailand, Vietnam and China) with the support of the Asian Development Bank (ADB), Philippines.

For realizing the goal of sustaining rural livelihoods and effective utilization of existing resources, a convergence (tendency to meet at a point) of activities mode was chosen. Adoption of convergence in APRLP is to improve rural livelihoods, which implies that all activities under APRLP should bring in betterment in rural livelihoods (APRLP, 2006b, 2007). For maximizing the efforts so as to meet strategic and practical livelihood concerns of the poor, small and marginal farmers, and women, the convergence system forms the strategy of APRLP. The APRLP has chosen the watershed as a logical unit for efficient management of natural resources collectively, and simultaneously thereby sustaining rural livelihoods, where the focus is on the scope and priorities for development of rural people.

The watershed as an entry point

For improving rural livelihoods, the watershed forms a logical unit for efficient management of natural resources, thereby sustaining rural livelihoods. A hydrological watershed is a delineated area from which the run-off drains through a particular point in the drainage system. Since soil and vegetation can also be conveniently and efficiently managed in this unit, the watershed is considered the ideal unit for managing the vital resources of soil, water and vegetation. Watershed management is the integration of technologies within the natural boundaries of a drainage area for optimum development of land, water and plant resources to meet the basic needs of people and livestock in a sustainable manner (Wani *et al.*, 2002, 2003a, 2005).

Integrated watershed management approach

The conventional watershed approach attempts to optimize the use of precipitation through improved soil, water, nutrient and crop management but lacks the strategy for efficient use of the conserved natural resources. In an agricultural watershed approach, management of water and land is most important. People and livestock being an integral part of the watershed, traditional watershed programmes alone, which are structure driven, cannot offer solutions to improve rural livelihoods. Although the watershed serves as an entry point, a paradigm shift is needed from these traditionally structure-driven watershed programmes to a holistic systems approach to alleviate poverty through increased agricultural productivity by environment-friendly resource management practices (Wani *et al.*, 2008b).

The watershed as an entry point should lead to exploring multiple livelihood interventions (Wani *et al.*, 2006a,b, 2007, 2008b). The overall objective of the whole approach being poverty elimination through sustainable development, the new community watershed management model fits into the framework as a tool to assist in sustainable rural livelihoods. For the development of rainfed-agriculture-based livelihoods, the community watershed model conceptually provides an envelope through which many of the steps for sustaining agriculture and agriculture-related activities can be implemented. The task is to intensify complex agricultural production systems while preventing damage to natural resources and biodiversity and to improve the welfare of the farmers through value addition and market linkages. Watershed management is the integration of technologies within the natural boundaries of a drainage area for optimum development of land, water and plant resources to meet the basic needs of the people and livestock in a sustainable manner.

ICRISAT's consortium model for community watershed management as shown in Fig. 12.1 espouses the principles of collective action, convergence, cooperation and capacity building (four Cs) with technical backstopping by a consortium of institutions to address the issues of equity, efficiency, economics and environment (four Es) (Wani *et al.*, 2006a).

The new integrated community watershed model provides technological options for management of run-off water harvesting, *in-situ* conservation of rainwater for groundwater recharging and supplemental irrigation, appropriate nutrient and soil management practices, waterway system, crop production technology, and appropriate farming systems with income-generating micro-enterprises for improving livelihoods while protecting the environment. The current model of watershed management, as adopted by the ICRISAT watershed consortium team, involves environment-friendly options and the use of new science tools, along with the concept of the consortium approach and emphasis on empowering farmers through capacity building. The model includes the consortium approach and adopts the concept of convergence in every activity in the watershed (Wani *et al.*, 2002, 2006a,b; Sreedevi *et al.*, 2004).

The Adarsha watershed (in Kothapally, Ranga Reddy district in Andhra Pradesh, India),

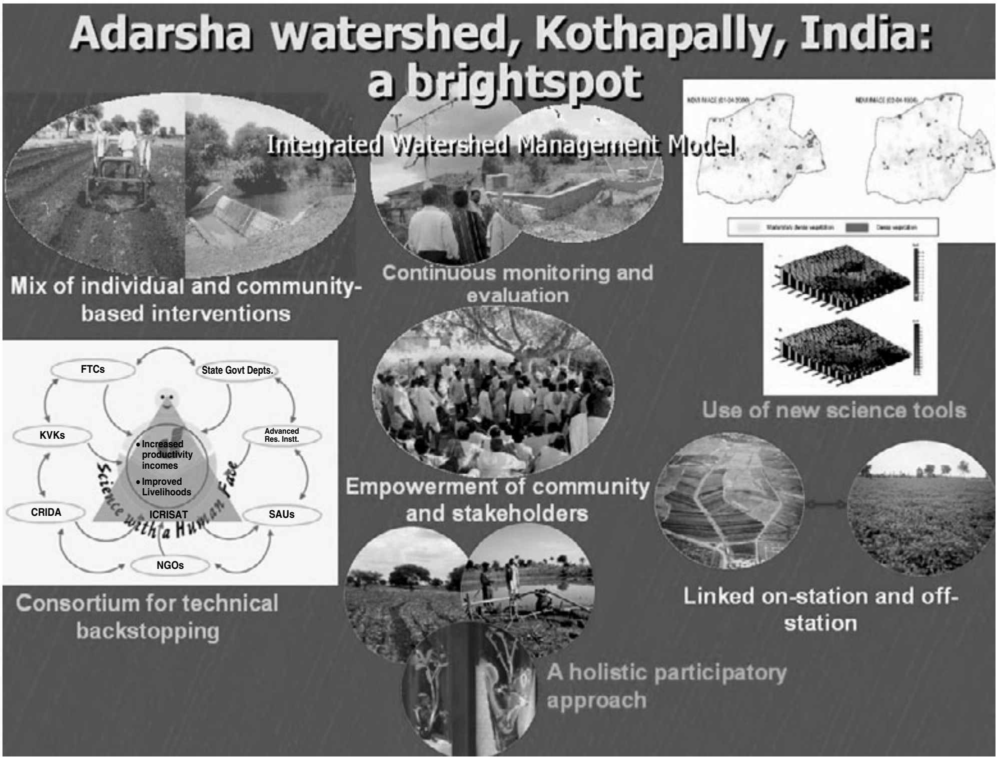


Fig. 12.1. Innovative farmers' participatory consortium.

led by the ICRISAT consortium, has clearly demonstrated increased crop productivity from rainfed systems through an integrated watershed management approach. APRLP's working mode to improve the rural livelihoods through the watershed approach has adopted the Adarsha watershed as an example of a more holistic vision that brings the concept of sustainability and eco-regionality and focuses on increased productivity and profitability of complex farming systems at the smallholder level.

Convergence in the watershed

Convergence in the watershed has evolved with the community watershed management model, which apart from the IGNRM strategy encompasses several other entities. By adopting a holistic watershed management approach, the community watershed is used as an entry point to converge and to explicitly link watershed development with rural livelihoods and effective poverty eradication and in the process identify policy interventions at micro-, meso-, and macro-levels (Fig. 12.2). Convergence can take place at different levels. Convergence at the village level requires facilitation of processes that bring about synergy in all the watershed-related activities. Scope for issues related to suitable processes for change in micro-practices, macro-policies, convergence, and information and management systems also formed part of the APRLP mandate. Socio-economic institutional and policy needs to increase adoption of improved options by the rural people are adapted in the convergence approach. The complex agricultural production systems were intensified while preventing damage to natural resources and biodiversity and improving the welfare of the farmers and landless rural poor. The activities in integrated watershed management approach where convergence mode works included:

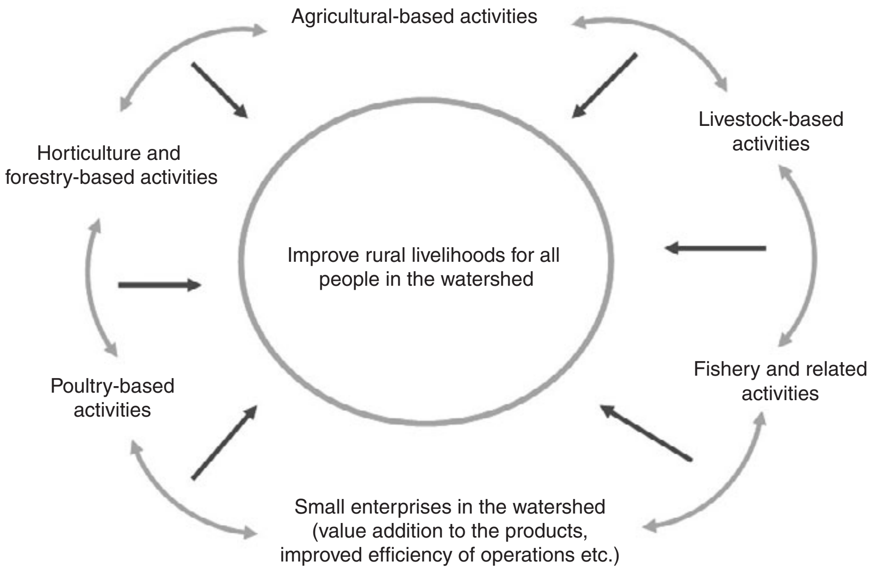


Fig. 12.2. Convergence in community watershed.

- Rainwater conservation and harvesting.
- Productivity enhancement.
- Soil conservation.
- Watershed development.
- Establishing village seedbanks through self-help groups (SHGs).
- Availability of quality seeds to farmers at reasonable rates.
- Processing for value addition (seed material, poultry feed, animal feed, grading and marketability, quality compost preparation).
- Livestock-based livelihood activities through improvement of breed, health and feed quality.
- Poultry rearing for egg and meat production and local hatching to provide chicks.
- Vermicomposting with cow dung, fodder waste and weeds, providing quality compost locally.

Participatory community watershed

The consortium model is a participatory community watershed system with a multi-disciplinary and multi-institutional approach, a process involving people who aim to create a self-supporting system essential for sustainability. The process begins with the management of soil and water, which eventually leads to the development of other capitals such as human, social, physical infrastructure and financial resources. However, large-scale community participation is essential since finally it is the people who have to manage their resources. Access to productive resources, empowering women, building on local knowledge and traditions, and involvement of local farmers or villagers in the local communities in watershed activities contributed to the success story at Adarsha watershed. Farmers' participation and involvement is critical in integrated community watershed management (Wani *et al*., 2003a; Sreedevi *et al*., 2004; Joshi *et al*., 2005) and it is complex and needs careful consideration. There is a need to harmonize working between existing institutions such as *panchayats* and watershed management and users' associations.

Strategies for integrated farm management

To achieve the goal of increased productivity in rainfed systems and enhance livelihoods, the following strategies are critical for integrated farm management practices:

- Need-based selection of watersheds to ensure that programmes are demand driven rather than supply driven, as is the case generally.
- Participatory approach involving different stakeholders (farmers, NGOs, local institutions (Krishi Vigyan Kendras (KVKs)), and regional research stations) for planning, execution and evaluation of project activities.
- A multi-institutional consortium approach for technical backstopping to empower farmers and develop human and institutional resources through capacity-building measures by integrating the activities of KVKs, Farmers' Training Centres, NGOs, research organizations and line departments of the state government for technical backstopping to undertake the action research at watershed level. Good and honest facilitator for effective and efficient functioning of the consortium.
- Productivity enhancement measures for increasing the farmers' incomes through *in-situ* conservation of soil and water, stress-tolerant high-yielding cultivars, improved crop, nutrient and pest management options, and equipment in addition to the normal soil and water conservation measures.
- Convergence of crop–livestock-based activities and other income-generating micro-enterprises in the watersheds by linking watershed development and research activities to increase the effectiveness of holistic watershed programmes through efficient use of conserved/harvested water and other natural resources for increasing production and incomes of the rural poor.
- Create awareness among NGOs and farmers about environment-friendly resource management options to minimize land degradation and improve natural resource base.
- Construction of small and low-cost water-harvesting structures throughout the topo-sequence to benefit all farmers, as against the large storage structures at the lower end of the watershed that benefit only a few, and thus address equity issues for water use.
- Complementary action-research designs for making effective links between on-farm problems and solutions to ensure the success of watershed development programmes by bringing together the knowledge gained through national and international experiences to the farmers.
- Networking of community-based organizations (CBOs) to achieve the common goals with appropriate incentives of increasing productivity and alleviating poverty.
- Participatory identification of farmer-acceptable crop cultivars to increase the systems' productivity in watersheds.
- Use of new science tools such as remote sensing (RS), information and communication technologies (ICTs), geographic information systems (GIS) and crop simulation models for efficient management of natural resources.
- Collective action through SHGs and micro-financing institutions to benefit voiceless vulnerable group members.
- Enrich human resources with special emphasis on women and youth to undertake income-generating activities through SHGs.
- Establish an ICT-enabled learning system for encouraging interactions among farmer groups to empower the community.
- Participatory monitoring and evaluation using new science tools as a measure for mid-course correction for enhancing impacts rather than for post-programme intervention.

The consortium approach enables the addressing of equity, gender, sustainability and improved livelihoods, which are the pillars of inclusive and sustainable development. Drivers of higher impacts in the community watershed are acute water scarcity, predisposition to work collectively for community development, good local leadership, tangible economic benefits to individuals, equal partnership, trust and shared vision among the stakeholders, transparency and social vigilance in the financial dealings, high confidence of the farmers, low-cost structures and equitable sharing of benefits, knowledge-based entry point activity, capacity building and empowerment of community, no free rides through subsidized activities for few individuals, and participatory and continuous monitoring and evaluation for mid-course correction (for details see Sreedevi *et al*., 2004; Shiferaw *et al*., 2006; Chapter 14, this volume).

Upscaling of Consortium Approach for Integrated Watershed Management

Based on the knowledge gained from Adarsha watershed, Kothapally, India, where the consortium approach was developed and piloted, the ICRISAT-led consortium scaled-out the approach in different states of India and selected provinces in Thailand, Vietnam and China. In India, the APRLP (supported by DFID, UK) adopted the watershed as an entry point for improving rural livelihoods in 500 pilot watersheds in five districts of Andhra Pradesh. The ICRISAT-led consortium established 150 watersheds (one nucleus; four satellites) as a pilot for the integrated watershed approach for improving rural livelihoods.

This project has joined the ongoing, statewide watershed programme to promote a change in focus so that the livelihoods of the poorest people in rainfed areas take centre stage. The project has fully financed all activities for 500 watersheds in five districts, Anantapur, Kurnool, Mahabubnagar, Nalgonda and Prakasam in Andhra Pradesh, which are semi-arid, drought-prone and among the poorest in the state. The project also provided extra finance to the Government of Andhra Pradesh for 'watershed plus' activities such as capacity building, productivity enhancement, livelihood support and convergence with other schemes and services, in 2000 more watersheds. In 2004–2005, the APRLP approach was extended to all the watersheds in all 22 rural districts of Andhra Pradesh.

APRLP approach

The convergence system forms the strategy of APRLP for maximizing the efforts so as to meet strategic and practical livelihood concerns of the poor, small and marginal farmers and women in the communities. Watershed management is used as an entry point to increase cropping intensity and also to rehabilitate degraded lands in the catchments with the aim of increasing productivity, enhancing biodiversity, increasing incomes and improving livelihoods. Such an approach demands integrated and holistic solutions from seed to final produce with involvement of various institutions and actors with divergent expertise varying from technical, social, financial, market, human resource development and so on (Wani *et al*., 2003c, 2007; Sreedevi *et al*., 2006).

As discussed earlier, in the Adarsha watershed, ICRISAT has clearly demonstrated increased crop productivity from rainfed systems through an integrated watershed management approach, which further helped in improving the soil quality and reducing the land degradation. Farmers adopted improved management practices such as sowing on a broadbed and furrow (BBF) landform, *Gliricidia* planting along bunds, integrated nutrient management (INM) treatment including inoculation with *Rhizobium* or *Azospirillum* spp., environment-friendly IPM, using improved bullock-drawn tropicultor for sowing and interculture operations, and *in-situ* conservation and harvesting of excess rainwater and storage for use as supplemental irrigation and for increased groundwater recharge (Wani *et al*., 2003a; Chapters 6 and 11, this volume). These innovations have been scaled up by APRLP in all the districts of Andhra Pradesh.

APRLP has also adopted the path with technical backstopping from research organizations like ICRISAT, the Central Research Institute for Dryland Agriculture (CRIDA), and Acharya NG Ranga Agricultural University (ANGRAU) for improving the rural livelihoods in the state of Andhra Pradesh. The concept of consortium is an integral part of the new integrated watershed management model.

Selection of watersheds and unique features in APRLP

APRLP devised a nine-point selection criteria (Table 12.1) for watersheds integrating natural resource degradation criteria with multiple deprivation criteria (social and material deprivation) in order to arrive at reliable indicators for both technical and social features. Micro- and macro-watersheds were identified and prioritized, based on the Sediment Yield Index indicating land degradation due to erosion and the dependability of precipitation and evapotranspiration, which depends on the variability and deviation of rainfall. Habitations were ranked according to the levels of degradation and the categories renamed as natural resource deprivation typologies.

Multiple deprivation criteria are indices of poverty, considering the multiple dimensions of poverty as reflected in deprivations of income, accessibility to services and social status. Since

Table 12.1. Nine-point selection criteria for selection of watersheds used in APRLP.

Parameters	Range	Mark	Weightage
% of small and marginal farmers	<25	5	
	>25–50	10	
	>50	15	15
% of SC/ST holdings	<10	3	
	>10–25	10	10
% of women organized in self-help groups and participating in the programme	<20	3	
	>20–50	5	
	>50	10	10
Status of groundwater (m)	<10	2	
	>10–15	3	
	>15	5	5
Andhra Pradesh Remote-sensing Application Centre (APSRAC) prioritization	Very low	6	
	Low	12	
	Medium	18	
	High	24	
	Very high	30	30
Livestock population	<1000	2	
	>1000–<2000	3	
	>2000	5	5
Number of families affected/involved in migration	<50	3	
	>50–<100	5	
	>100	10	10
Contiguity	Yes	5	
	No	0	5
Availability of fallow/wasteland and common property resources for the poor to utilize usufruct (%)	<10	3	
	>10–<20	5	
	>20	10	10
Total			100

APRLP takes a holistic view of people towards their livelihoods and opportunities, it sought to integrate the indices of natural resource degradation and multiple deprivation, and a matrix was drawn up where each was given equal importance, while selecting watersheds.

A probation period of up to 18 months was made mandatory in watersheds, during which the major activities were the preparation of capacity-building plans for primary and secondary stakeholders and the preparation of strategic (perspective plan for 5 years) and annual action plans. In each watershed 50 ha of land was selected as an entry point, out of which 20–30 ha of land belonging to small and marginal communities were selected for the treatment during the probation phase. The success of the probation phase was assessed using a set of agreed objective performance indicators (Table 12.2) by the community themselves, by which the project empowered the community and instilled a sense of ownership of the project, leading to its sustainability. APRLP adopted a site-specific and farmer-friendly participatory net planning (PNP) approach for preparing action plans for the individual farm holdings. Similarly, the poorest of the poor are identified through participatory situational analysis and wealth ranking of different households, based on their social and economic conditions.

Operationalizing APRLP–DFID–ICRISAT watersheds

A coalition of partners consisting of CRIDA, ANGRAU, National Remote Sensing Agency

Table 12.2. Parameters assessing the success of the probation phase for new watersheds in APRLP, Andhra Pradesh, India.

Item	Activity	Expected outcome
Situation analysis	Conducting participatory situation analysis	Strategic action plan of watershed (for 5 years)
	Conducting participatory rural appraisal	Probation-phase action plan
	Situational analysis of ground conditions	Livelihood action plan
	Wealth ranking exercise	Identification of poorest of the poor
Capacity building	Capacity needs assessment survey	Capacity-building plan of watershed incorporated in the district-level calendar
	Organizing mandatory training for community-based organizations (SHGs, user groups, watershed committees, watershed associations) and project-implementing agency/watershed development team	Completion of mandatory training of: • Project-implementing agency/watershed development team at MANAGE • SHGs /user groups/watershed committees at district level
	Identification and training of paraworkers – agriculture, animal husbandry, health, etc.	At least one paraworker for agriculture, animal husbandry from each watershed village trained
Consolidating SHGs	Categorizing existing SHGs as per District Rural Development Agency norms	• Self-monitoring through the Participatory Situational Analysis charts • About 50% of SHGs in 'A' category or show upward trend
	Organizing poor families who had not joined any SHGs into new SHGs	About 50% of target population organized into SHGs
	Promoting federation of SHGs into village organization	About 70% of SHGs federated into village organization
	Linking with revolving fund/bank loan	About 50% of SHGs linked with banks
Village organization	If it does not exist, then forming of village organization	Constitution of village organization if it does not exist
	If it already exists, ensuring linkage with newly formed SHGs	• Village organization strengthened to show improvement in category and scores 60 marks as per defined norms • Documentation on functioning process of village organization • Signing MoU with village organization
	Linking with livelihood fund	• Finalization of livelihood plan • Approval for the release of Livelihood Revolving Fund
Identification of probation-phase area, say 50 ha	Preparing action plan for probation area • Preferable location – ridge/valley • Area type – private land of about 25–30 ha (poor, marginal/small farmer) and common land of about 25–30 ha	• Watershed implementation should start from ridge to valley • Priority to common property resource • No work on private lands of large/medium farmer should take place till lands of marginal/small farmers get saturated
	Integrating with annual/strategic plan	Preparation of perspective plan
	Forming user groups	2–3 user groups formed
	Planning for low-cost structures	Priority to cost-effective structures
	Collection of contribution	Identification and evaluation of natural leaders and SHGs having potential for converting to watershed committees
Promotion of common pool resources	Plantation on common lands	Identification of common lands for plantation activities
	Accessibility to poor	• Usufruct rights to the poor • MoU for usufruct rights to the poor

(NRSA), Drought Prone Area Programme (DPAP) (now District Water Management Agency (DWMA)), Department of Agriculture (DoA), Project Implementing Agencies (PIAs), APRLP Programme Support Unit and ICRISAT was operationalized through a set of roles and shared responsibilities with a common vision. The emphasis was on empowerment of the community and gender equity through knowledge-based technological and institutional interventions, targeting multiple development constraints. The representative benchmark watersheds were identified for testing the technological findings. In the three target districts (Mahabubnagar, Kurnool and Nalgonda) of Andhra Pradesh, 50 watersheds (10 nucleus and 40 satellite) were selected based on several criteria: (i) representative typology; (ii) extent of rainfed area; (iii) productivity levels; and (iv) willingness of farmers to participate in the test sites for implementing the project activities (ICRISAT, 2006a). An additional 100 watersheds were added later. The nucleus watersheds served as the sites for undertaking action research for development and critical monitoring and also as sites of learning where farmers conducted experiments with improved soil, water, crop, nutrient and pest management options with technical backstopping from the consortium partners.

The farmers from nucleus watersheds, when empowered, became trainers to fellow farmers in both nucleus and satellite watersheds, while the PIAs empowered and developed as master PIAs and trained other PIAs in the districts. A detailed baseline socio-economic household survey was conducted in selected nucleus watersheds through participatory rural appraisal, a structured questionnaire and secondary data to study major socio-economic and biophysical constraints for sustainable crop production and to document detailed baseline data for impact monitoring at the end of the APRLP project in each village.

Equity issues were addressed appropriately while preparing action plans for sharing benefits from the interventions. Similarly, micro-enterprises had been promoted under plus activities to generate income for the communities during the off-season. This also reduced migration of rural people during the non-agricultural season to urban areas. A microfinance component had given priority to poor communities (SHGs) by linking local microcredit institutions for generating their revolving funds and for sustainability.

Knowledge-based entry point – widespread micronutrient deficiencies in SAT soils

The ICRISAT consortium team assessed 3622 soil samples from the farmers' fields in different states of India (Andhra Pradesh, Karnataka, Rajasthan, Madhya Pradesh, Gujarat and Tamil Nadu) and observed widespread deficiencies of sulfur (S), zinc (Zn) and boron (B), along with total nitrogen (N) and phosphorus (P) (Table 12.3) (Sahrawat *et al.*, 2008). For rapport building – knowledge-based entry point activity, for example – the results of the soil analysis were presented in the *gram sabhas*, and the importance of soil analysis and nutrient deficiencies in crop production were discussed (Fig. 12.3). A large number of farmers were convinced about the importance of balanced nutrition in crop production and came forward as volunteers to evaluate the INM options.

Table 12.3. Percentage of farmers' fields deficient in soil nutrients in different states of India.

State	No. of farmers' fields	Org. C (%)	Nutrients (mg/kg soil)				
			Av. P	K	S	B	Zn
Andhra Pradesh	1927	84	39	12	87	88	81
Karnataka	1260	58	49	18	85	76	72
Madhya Pradesh	73	9	86	1	96	65	93
Rajasthan	179	22	40	9	64	43	24
Gujarat	82	12	60	10	46	100	82
Tamil Nadu	119	57	51	24	71	89	61
Kerala	28	11	21	7	96	100	18

Fig. 12.3. Scientists explaining results of soil analysis to villagers in a *gram sabha* in a village at Palem, Mahabubnagar, Andhra Pradesh, India.

Land and water management

In drought-prone areas *in-situ* rainwater conservation measures improve the security for growing the crops. The approach has been to store as much rainwater in the soil as possible before channelling run-off from the fields for storage in the tanks. The bullock-drawn tropicultor, which is referred to as the poor man's tractor, provides all the help to undertake timely land preparation operations. Farmers have evaluated the following landform treatments:

- Flat sowing on contour.
- Flat sowing on contour and a dead furrow at 10–15 m distance.
- Planting on ridges.
- Broadbed and furrows on 0.4–0.8% grade.

About 1000 farmers in nine nucleus watersheds evaluated improved crop and soil management options in their fields with the technical support. Several farmers in nucleus watersheds have sown sole and intercrops in lines along with fertilizers using tropicultors (Fig. 12.4).

Integrated nutrient management (INM)

On the basis of soil test results, farmers used micronutrient amendments on various crops such as mung bean, sorghum, maize, pigeonpea, castor and groundnut. In spite of drought in 2002, the farmers in Nalgonda district, Andhra Pradesh recorded 17–125% increase in mung bean yield (with 44% more yield, i.e. 1110 kg/ha versus 770 kg/ha) in their village in spite of the prevailing drought condition during the season. Farmers recorded 13–230% increase in maize yields with an average increase of 72% over the base yield of 2980 kg/ha; the increase in castor yields was 21–70% with an average increase of 60% over the base yield of 470 kg/ha. Similarly groundnut yield increased by 28% over the base yield of 1430 kg/ha.

Based on the experience in the first year, participatory R&D trials were designed to study the response of crops like mung bean, sorghum, maize, pigeonpea, castor and groundnut to each deficient nutrient over farmers' nutrient inputs as well as to secondary and micronutrients with optimum N and P nutrients. Good response has been observed in maize, sorghum, mung bean and groundnut not only to combined application of S, B and Zn but also to individual application of these nutrient elements (Table 12.4). The balanced nutrient supply resulted not only in significant increases (70–119%) in grain production but also in substantial additional incomes (Table 12.5).

Fig. 12.4. Sowing with a tropicultor.

Table 12.4. Yield and total dry matter (TDM) of different crops based on response to nutrients during the rainy season, 2003 in APRLP watersheds.

Crop	No. of farmers	Control (C)	Sulfur (S)	Boron (B)	Zinc (Zn)	C+SB+ Zn	C+NP+SB +Zn	SE	CV (%)
Maize grain (kg/ha)	24	2,790	3,520	3,710	3,710	4,140	4,880	466	12
% increase over control			26	33	33	49	75		
Maize TDM (kg/ha)		6,370	7,650	8,120	7,950	9,060	104,00	947	12
% increase over control			20	27	25	42	63		
Groundnut pod (kg/ha)	30	830	930	1,000	1,050	1,230	1,490	134	12
% increase over control			12	20	27	48	78		
Groundnut TDM (kg/ha)		2,920	3,150	3,453	3,590	4,140	4,730	333	9
% increase over control			8	18	23	42	62		
Mung bean grain (kg/ha)	6	900	1,210	1,130	1,320	1,390	1,530	114	9
% increase over control			33	24	46	54	70		
Mung bean TDM (kg/ha)		2,900	4,140	3,840	4,510	4,840	5,410	335	8
% increase over control			43	32	55	67	86		
Sorghum grain (kg/ha)	6	900	1,190	1,160	1,330	1,460	1,970	190	14
% increase over control			32	29	47	62	119		
Sorghum TDM (kg/ha)		4,800	5,460	5,480	6,420	6,640	8,030	790	13
% increase over control			14	14	34	38	67		

Table 12.5. Economic returns through application of micronutrients to different crops during 2003.

	Economic returns (Rs/ha)			
Particulars	Maize	Groundnut	Mung bean	Sorghum
Farmers inputs (FI)	13,930	12,490	13,570	4,510
FI + B	18,350	14,850	16,710	5,970
FI + S	17,230	13,650	17,770	5,620
FI + Zn	17,480	14,780	18,760	5,590
FI + B + S + Zn	19,430	16,850	19,290	5,730
FI + B + S + Zn + NP	21,770	19,520	20,330	7,170

Soil organic matter: an important driver of increased productivity

Soils in the dryland tropical areas are marginal to irrigated. Assessment of the fertility status of farmers' fields showed that almost all farmers' fields sampled were low in organic carbon (Sahrawat *et al.*, 2008). It is, however, recognized and emphasized that the productivity of tropical drylands is low due to water shortages. However, rather than water quantity per se, management of available water with enhanced water use efficiency is a problem and soil fertility is an important limitation (Wani *et al.*, 2008c; Chapter 2, this volume).

Farmyard manure is in short supply and is generally applied to high-value irrigated crops in drylands. *In-situ* generation of N-rich organic matter by growing *Gliricidia sepium*, *Cassia semia* and other N_2-fixing legumes on contour and property bunds and maintaining as shrubs helps in adding organic matter to the soil (Fig. 12.5). *Gliricidia sepium* is drought tolerant, sturdy under varying temperature conditions and animals do not like it. Once established, from the second year onwards *G. sepium* loppings provide 30–50 kg N/ha, which is largely fixed from the atmosphere, and other plant nutrients are also recycled from deeper soil layers. In addition it provides valuable organic matter, much needed in the tropics for maintaining soil fertility. The SHGs grew the nurseries of *Gliricidia* in the villages as an income-generating micro-enterprise and provided the plants for planting on the field bunds.

Vermicomposting

Large quantities of organic wastes are generated regularly in farms as well as in houses. Disposal of such residues is difficult and generally becomes a serious problem. Most of the organic waste is either burned or used as land fillings. These residues contain valuable plant nutrients and can be effectively recycled and used for increasing the agricultural productivity. Earthworms convert the residues into a valuable source of plant nutrients by feeding on the organic material and excreting valuable organic manure. The role of earthworms is to improve soil fertility and soil health. They eat farm residues and vegetable peelings and convert these into an N-rich compost called vermicom-

Fig. 12.5. *Gliricidia* plants on field bund conserving soil and generating nitrogen-rich organic matter.

post. Vermicompost increases the water-holding capacity of the soil, promotes crop growth, increases production and improves food and fodder quality. Generally, rock-phosphate-enriched vermicompost contains 1.0–1.4% N, 0.6% P, 0.7% potassium (K) and also many other micronutrients (Ca, Mg, Cu, Fe, Zn) which are very important for increasing crop productivity and maintaining soil quality.

These alternate sources supply sizeable quantities of nutrients, reducing the need for huge quantities of costly fertilizer, and also provide an alternate source of income for the women SHGs as a micro-enterprise (Fig. 12.6). However, suitable capacity building and awareness measures are needed to harness multiple benefits such as recycling valuable plant nutrients, disposal of organic wastes through environment-friendly methods and generating additional income for women SHGs.

A commercial model of vermicomposting developed at ICRISAT, Patancheru consists of four chambers enclosed by walls (1 m high, 1.5 m wide, total of 4.5 m long). The walls can be made up of different materials such as normal bricks, hollow bricks, Shabad stones, asbestos sheets or locally available rocks. The partition walls contain small holes to facilitate the easy movement of earthworms from one chamber to another (Fig. 12.7). The outlet provided at the

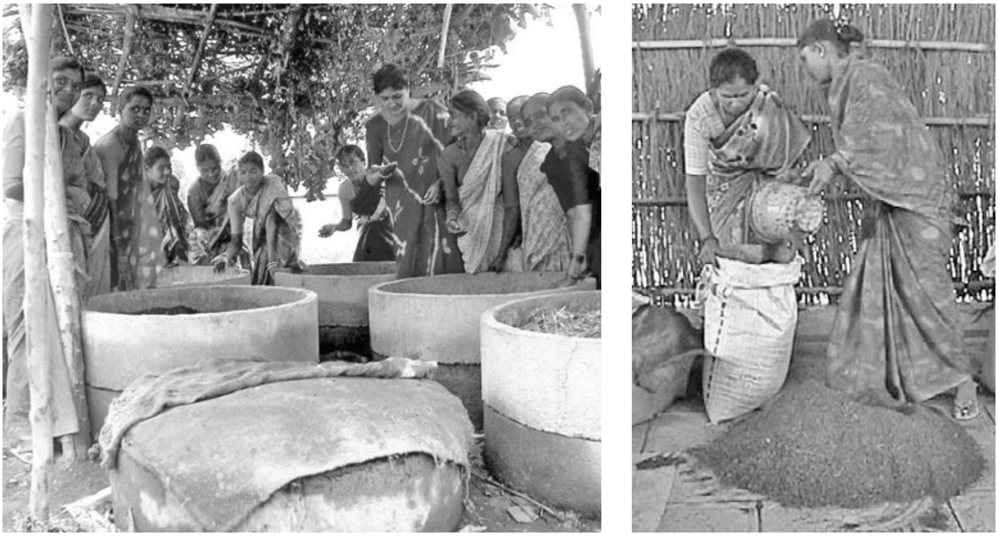


Fig. 12.6. Vermicomposting by women's self-help groups in a village in Andhra Pradesh, India.

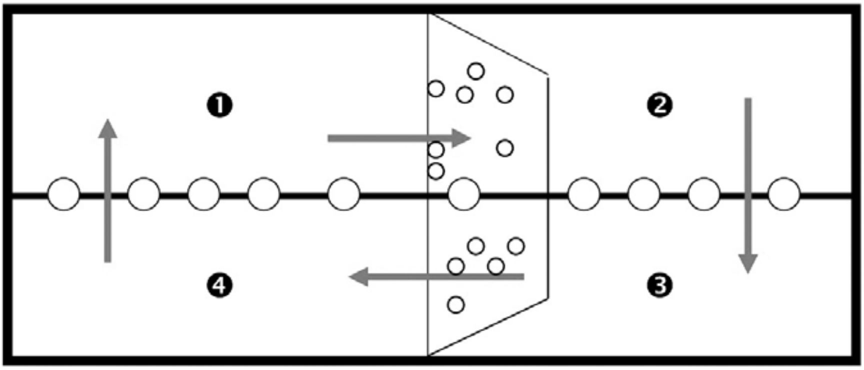


Fig. 12.7. Commercial model of vermicomposting.

corner of each chamber helps collect excess water, which can be reused. The four components are filled with plant residues one after another and earthworms are released once the first chamber is filled. Once the contents in the first chamber are decomposed the earthworms move to the second chamber and so on. This facilitates continuous supply of vermicompost, saving on labour and introduction of earthworms each time.

Integrated pest management

Crop production in the semi-arid tropics is severely threatened by increased difficulties in controlling insect pests and diseases of crop plants, as pests are developing resistance against the pesticides used, which results in an increase in cultivation costs and environmental problems with pesticide residues. The IPM measures include use of improved pest-tolerant cultivars, pest monitoring, use of biopesticides and plant-based pesticides, cultural practices such as use of trap crops and need-based use of chemicals. The major purpose of monitoring is to ensure protection of crops of the partner farmers in the watersheds from insect pests using scientifically accepted and economically viable field-applicable practices (Fig. 12.8). This was achieved by: (i) familiarizing the partner farmers on scouting for insect pests and monitoring their population; and (ii) using the data/information thus collected for decision making on spray material for protection against the insect pest threatening a given crop.

Shaking off larvae of *Helicoverpa armigera* from pigeonpea stems and manual killing of *Spodoptera* larvae on castor leaves were laborious but effective methods. Neem fruit extract (25 kg/ha) in boiling water was recommended for control of semilooper on castor and *Helicoverpa* on pigeonpea, when the larvae were in early instar stages. As a continuous effort to enhance capacity building, community video shows on IPM in groundnut, pigeonpea and chickpea were organized in these villages. In north-east Thailand, Tad Fa watershed farmers use low-cost sugarcane molasses kept in open plastic bottles to attract insects and control the pests. In vegetable plots, 700 ml capacity bottles with two side openings are filled with molasses and placed at 30 cm above ground level (Fig. 12.9). The insects are attracted by molasses, get trapped and die. About 3–73% damage is caused in cabbage fields due to loopers, leaf-eating beetles and cabbage cutworms (Table 12.6). At Wang Chai and Tad Fa watersheds in north-east Thailand, farmers are successfully and effectively using

Fig. 12.8. Farmers in India monitoring pest population with pheromone traps.

Fig. 12.9. Simple IPM system installed in a cabbage field in north-east Thailand.

Table 12.6. Estimation of damage to cabbage crop by insects without using IPM technique in Thailand[a].

Adult insects (worms source)	Insects trapped in bottle (no.)	Total worms (eggs) that could have been produced by trapped insects (no.)	No. of worms to potentially damage one plant completely	Degree of damage without IPM (%)
Cabbage loopers	165	123,750	150	15
Cabbage cutworms	115	28,750	7	73
Leaf-eating beetles	108	15,050	100	3
Total	388	167,550	257	91

[a]Calculated based on 25 IPM trap sets used in 5,600 cabbage plants.

molasses to control pests in vegetable fields (Table 12.6). Similarly, in China watersheds, farmers are successfully using light traps and tobacco waste to control pests in vegetable fields in Xiaoxincun watershed, Yuanmou in south China.

Crop intensification and diversification

Farmers' participatory selection of improved varieties

One of the important weak links in increasing crop productivity is poor crop stand due to poor seed quality and use of traditional varieties. Watershed farmers were empowered through technical backstopping, and the dependency of farmers on subsidies was minimized. The farmers selected improved cultivars and established village seedbanks. To build the stocks of seeds of improved crop cultivars in the watershed villages, activities on continued strengthening of village-based seedbanks were taken up by increasing the quantity of breeders' seeds of different crops.

The empowered farmers and SHG members operated village seedbanks based on the demand from the farmers who had identified suitable cultivars through participatory R&D. The SHGs buy back the seeds of varieties (not the hybrids) produced under the technical guidance of the consortium partners. The improved seeds of high-yielding varieties of all the crops proved remunerative because of their high yields (Table 12.7). Similarly, farmers in Rajasthan, Madhya Pradesh and Karnataka have selected cultivars and established village seedbanks. In Andhra Pradesh, the government has scaled-out the village seedbank initiative by institutionalizing the concept with revolving funds provided by the government.

Yield maximization trials

Farmers' yields are two- to fivefold lower than the potential yields realized at research stations or obtained by progressive farmers (Rockström *et al*., 2007; Wani *et al*., 2008a). Yield maximization in participatory R&D trials on prominent crops (castor, pearl millet, maize, sorghum, pigeonpea, groundnut, soybean and sunflower) with best-bet options (improved seed, integrated nutrient and pest management and improved crop husbandry practices) resulted in spectacular yield advantages in sorghum (35–257%), maize (30–174%), pearl millet (72–242%), groundnut (28–179%), pigeonpea (97–204% in sole and 40–110% in intercropping) and mung bean (42–111%) crops despite a not so favourable cropping season due to prolonged early and mid-season drought (Tables 12.8–12.12 and Fig. 12.10).

Crop intensification in watersheds

Double cropping (sorghum–chickpea, maize–chickpea) introduced in the traditionally *rabi* (post-rainy)-season-cropped vertisol areas of Kurnool and Nalgonda districts (850 ha) and intercropping (sorghum/pigeonpea, castor/pigeonpea, groundnut/ pigeonpea, groundnut/pearl millet, cotton/pigeonpea) in the alfisol areas (2500 ha) of Mahabubnagar, Nalgonda and Kurnool (Fig. 12.11) gave substantial yield advantages and captured farmers' interest, and considerable area increase is envisaged.

Water management: key investment for diversification of agricultural income

Established but incomplete evidence indicates that off-farm employment in rural areas usually expands parallel to agricultural growth. It has been estimated that a 1% growth in agricultural yields brings about a 0.5–0.7% reduction in the number of poor (World Bank, 2005). Thus rural employment, both on-farm and off-farm, is strongly conditioned by the rate of agricultural growth.

A recent study in the developed Rajasamadhiyala watershed in Gujarat, India

Table 12.7. Farmer participatory selection of groundnut varieties in Karivemula in Andhra Pradesh, India during 2003.

Improved practice		Farmer practice			
Variety	Yield (kg/ha)	Variety	Yield (kg/ha)	% Increase	Increase in income (Rs/ha)
ICGS 11	1730	TMV-2	1140	52.0	8850
ICGS 76	1480	TMV-2	900	64.0	8700
Mean	1605		1020	58.0	8775

Table 12.8. Mung bean yields as affected by best-bet options in Nalgonda district in in Andhra Pradesh, India during rainy season 2003.

	Grain yield (t/ha)		
Watershed	Improved practice[a]	Traditional practice[b]	Yield advantage (%)
Nandyal Gudem	1.42	1.00	42
Atmakur	1.44	0.92	57
P. Suryapet	2.15	1.02	111
Mean	1.67	0.98	70

[a] Improved seed, integrated nutrient and pest management, and targeted crop husbandry; [b]Farmers' normal crop husbandry practices with or without improved seed.

Fig. 12.10. Performance of crops with best-bet options in community watersheds in Karnataka, India.

Table 12.9. Pearl millet yields as influenced by best-bet options in Kurnool district in Andhra Pradesh, India during rainy season 2003.

		Grain yield (t/ha)		
Crop	Watershed	Improved practice	Traditional practice	Yield advantage (%)
Pearl millet	Devanakonda	2.29	1.33	72
	Obulapuram	2.50	0.73	242
	Madhapuram	1.62	0.59	175

revealed that public investments in rainwater harvesting enabled individual farmers to invest in digging open wells and bore wells, pump sets, sprinkler sets and drip irrigation systems in addition to investments in fertilizers, and improved pest and disease management options (Sreedevi *et al.*, 2006; Wani *et al.*, 2006a). Integrated watershed development triggered a shift towards commercial cereal crop production, such as maize, whereas in the surrounding villages without watershed development, farmers continued to grow low-value cereals like sorghum. In addition, farmers put more area under vegetables and horticultural crops in the developed watershed village, Kothapally, as compared with the surrounding non-project villages in Andhra Pradesh (Wani *et al.*, 2006b) (Fig. 12.12). A prerequisite for such a diversification is the access to markets. In India the output from rainfed agriculture has in many areas increased

Table 12.10. Maize yields as influenced by best-bet options in Nalgonda and Mahabubnagar districts in Andhra Pradesh, India during rainy season 2003.

Watershed	Grain yield (t/ha) Improved practice	Grain yield (t/ha) Traditional practice	Yield advantage (%)
Nalgonda			
Kacharam	4.40	1.68	162
D. Gudem	2.96	2.25	32
K. Gudem	3.83	2.34	64
Sadhuvelli	4.02	2.84	42
Gouraipalli	3.85	1.91	102
Mean	3.81	2.20	73
Mahabubnagar			
Sripuram	5.76	4.44	30
Uyyalawada	3.90	2.02	93
Aloor	4.37	2.40	82
Nallavelli	5.81	4.27	36
Vanapatla	5.92	4.31	37
Naganool	5.64	4.20	34
Malleboinpally	3.89	1.62	140
Sripuram	8.32	3.04	174
Naganool	8.00	3.12	156
Vanapatla	8.39	5.52	52
Gollapally	4.73	3.56	33
Mean	5.88	3.50	68
Grand mean	5.24	3.10	69

Fig. 12.11. Pearl millet/groundnut intercropping in Devanakonda, Andhra Pradesh, India.

Table 12.11. Groundnut yields as influenced by best-bet options in Nalgonda and Kurnool districts in Andhra Pradesh, India during 2003.

Groundnut	Watershed	Grain yield (t/ha) Improved practice	Grain yield (t/ha) Traditional practice	Yield advantage (%)
	Nalgonda			
	Nemmikal	1.98	0.75	164
	P.Suryapet	1.36	0.83	64
	Gattikal	1.00	0.53	89
	Nassempet	1.09	0.58	88
	Mean	1.36	0.67	102
	Kurnool			
	Karivemula	1.44	0.85	69
	Karidikonda	1.78	1.02	75
	Jilledabudakala	1.21	0.74	64
	Devanakonda	1.99	1.55	28
	Burrakunta	1.14	0.73	56
	Karivemula	2.37	0.85	179
	Karidikonda	1.66	1.16	43
	Jilledabudakala	1.15	0.81	42
	Burrakunta	2.23	1.47	52
	Venkatapuram	0.81	0.46	76
	Rallakottur	1.55	1.03	50
	Mean	1.58	0.97	62
	Grand mean	1.52	0.89	70

Table 12.12. Sorghum yields as influenced by best-bet options in Nalgonda and Mahabubnagar districts in Andhra Pradesh, India during 2003.

Sorghum	Watershed	Grain yield (t/ha) Improved practice	Grain yield (t/ha) Traditional practice	Yield advantage (%)
	Nalgonda			
	Sadhuvelli	2.68	1.59	69
	Dharmareddigudem	2.14	1.58	35
	Mean	2.41	1.59	52
	Mahabubnagar			
	Burreddypally	1.92	0.94	104
	Gangapuram	1.47	0.93	58
	Burreddypally	3.18	0.89	257
	Nandipet	3.07	0.97	217
	Gollapally	1.65	0.98	68
	Mean	2.26	0.94	140
	Grand mean	2.30	1.13	104

rapidly and at the same pace as in irrigated areas, including widespread adoption of high-yielding varieties in rainfed areas (Kerr, 1996).

Similarly, in many parts of Tanzania, rainwater harvesting has enabled farmers in semi-arid areas to upgrade rainfed farming by shifting from the cultivation of sorghum and millet to rice or maize, with follow-up legume crops that exploit residual moisture in the field. Currently, production of rice in semi-arid areas using rainwater harvesting accounts for over 35% of the rice produced in the country (Gowing *et al*., 1999; Meertens *et al*., 1999). Most importantly, upgrading rainfed farming through rainwater harvesting has enabled farmers to grow a marketable crop in dry areas,

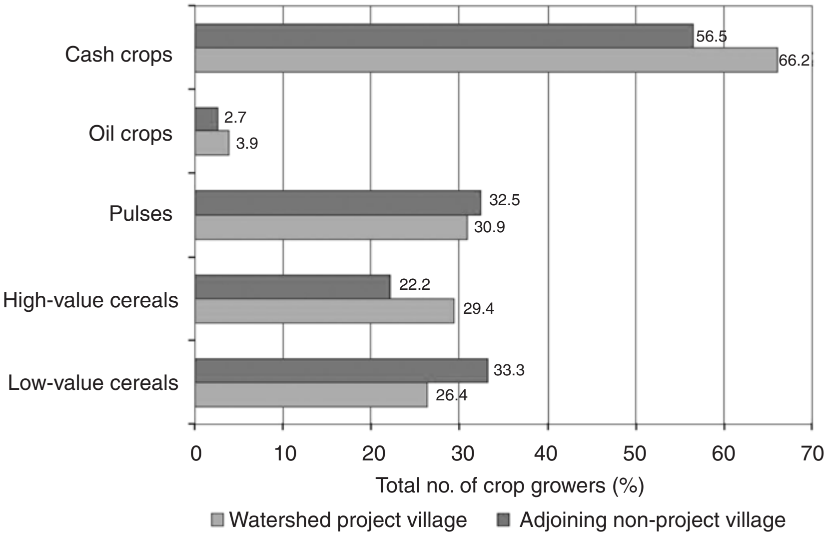


Fig. 12.12. Income stability and resilience in Kothapally, Andhra Pradesh, India.

thus providing opportunity for poverty reduction (Rockström *et al.*, 2007). In China, rainwater harvesting and storage on a small scale enabled farmers to grow vegetables and market collectively to earn more income (see Box 12.1).

Multiple benefits of farm-scale water management

Investments in water management in rainfed systems can have important additional benefits due to the multiple roles of water for livelihoods and health. Benefits from rainwater in supporting all forms of biomass growth of cultivated crops, pasture for livestock, non-cultivated food plants, and fuel and construction wood indicate that rainwater plays an important role in determining overall resilience of rural communities practising rainfed agriculture. Rural livelihoods are also strongly dependent on non-agricultural income, i.e. other livelihood strategies (remittances, seasonal off-farm work, rural complementary sources of income, etc.), which reduce vulnerability to rainfall variations (Rockström *et al.*, 2007). A study in East Africa shows that strategies for poverty reduction to meet the Millennium Development Goals require investments that promote productivity growth in: (i) major staples, which were found to be key for overall economic growth and poverty reduction. Since rainfed systems dominate the production of staples, this is proof of the importance of investing in the upgrading of rainfed systems; (ii) the livestock subsector, which consists of predominantly rainfed systems, is a key livelihood source for the people in the SAT region; and (iii) non-farm rural enterprises, especially those linked to value-adding processing of crop and livestock produces (ASARECA-IFPRI, 2005).

Apart from livestock enterprises, there are other options available for generating more benefits from systems such as forests and rangelands, which deplete rainwater naturally. They include investments to further add value to rain, e.g. the development of micro-enterprises associated with natural resources such as vermicomposting, nursery raising, biodiesel plants, oil extraction and value addition through processing of farm produce. These activities ensured diversified livelihood options for women as well as youth and provided resilience during the drought years (Wani *et al.*, 2003b, 2006b; Joshi *et al.*, 2005). Micro-enterprises benefited women and vulnerable groups in the society and addressed equity issues in rainfed areas (Box 12.2).

Box 12.1. Contribution to women's development.

Women's tenacity in householding is remarkable. In the watershed villages, women's propensity to work against all odds is shown in the management of household consumption and production under conditions of increasing poverty.

Lakshmi, a poor resident of Kothapally village, Andhra Pradesh, India, eked her livelihood as a farm labourer until she was introduced to vermicomposting, i.e. converting degradable garbage, weeds and crop residues into valuable organic manure using earthworms. She earned US$36 per month from this activity. She has also inspired and trained 300 peers in 50 villages of Andhra Pradesh. Lakshmi has also achieved a singular recognition by becoming a Fellow of the Jamsetji Tata National Virtual Academy for Rural Prosperity for her achievement of empowering women members.

Subhadrahbi is the key person in the change in the role of women and the transformation of Powerguda, a tribal village in Andhra Pradesh, into one of self-sufficiency. She pioneered the integrated watershed management approach and biodiesel enterprise, specifically *Pongamia* nursery raising and extraction of oil in the village. With this, her women's group sold carbon credits to the World Bank and gained worldwide accolade.

A woman in Wang Chai watershed, Thailand who had the chance to be part of a cross-visit sponsored by the watershed project learned much about cooperative work. This paved the way for the various self-help groups organized, such as fish sauce, soap making, shampoo and fish feed.

In Addakal *mandal*, India, a group of 500 women from 17 villages federated to form the *Mahila Samaikhya*. To date, they operate a bank, a resource centre for training and a knowledge hub. They are connected worldwide through information technology and facilitated empowerment of other women, especially of their district.

These cases epitomize how women in certain situations and relationships can wield power and use possibilities for maneuvering to achieve better livelihoods. Watershed projects provided the platform for creativity and innovations without jeopardizing social norms.

Box 12.2. Poultry farming leading the way to prosperity in Lucheba.

Mr Peng Fay Ou, a normal farmer with a 1 ha landholding in Lucheba watershed in China, has seven members in the family and was earning 3000 CNY per year. However, with the watershed project interventions his agricultural income has been raised by threefold to 10,000 CNY per year and it is largely owing to growing vegetables three times in a year using the harvested rainwater. The way Mr Peng Fay has moved out of poverty, leveraging the allied sector activities through increased income is exemplary. He has 200 chicks and plans to sell these when they are 70 days old. He is expecting 30 CNY per bird and a total income of 6000 CNY. He has two female pigs, seven male pigs and 15 piglets, which he sold at 1500 CNY. He also has one buffalo. His income has increased to 4000–5000 CNY per year. In this village he says that his family is one of the few (15) families having higher income, although the income of all the families has substantially improved due to the project activities.

Mr Chen Shao Bao is another enterprising farmer, who has 1500 chicks in his unit for the first time. He said that income from pigs was less and they decided to invest more in poultry to earn more income. From pigs he got 10,000 CNY total income whereas by investing 4000 CNY in chicks he will get 7000 CNY net income in less time. He plans to have a 20-day cycle for the poultry. His mother Liu Yun Zhen helps him in taking care of the poultry. His family is a joint family with eight members. Similarly there are ten other farmers who are rearing poultry in this group of 44 farmers.

Run-off and soil loss from the APRLP watersheds

At each of the ten watersheds of APRLP in Andhra Pradesh, a digital run-off recorder and microprocessor-based automatic sediment sampler were installed, which measured run-off and soil losses. Among the ten watersheds, considerable variations in seasonal run-off, peak run-off rate and soil loss were recorded (Table 12.13). The highest seasonal run-off of 68.9 mm (12.8% of the seasonal rainfall)

Table 12.13. Rainfall, run-off, peak run-off rate and soil loss in APRLP watersheds during 2003.

District	Nucleus watershed	Seasonal rainfall (mm)	Seasonal run-off (mm)	Peak run-off rate (m^3/h/ha)	Soil loss (t/ha)
Mahabubnagar	Appayapally	540	69	58.7	1.04
	Malleboinpally	654	55	57.6	NA[a]
	Mentapally	335	29	10.8	0.28
	Sripuram	474	46	25.2	0.98
Nalgonda	Kacharam	700	30	7.2	0.58
	Tirumalapuram	474	17	79.2	0.53
	Nemmikal	695	75	82.8	1.45
Kurnool	Devanakonda	502	79	370.8	0.78
	Karivemula	320	25	61.2	0.69
	Nandavaram	354	Nil	Nil	Nil

[a] NA = data not available.

was recorded at Appayapally watershed in Mahabubnagar district and no run-off was recorded from Nandavaram watershed in Kurnool district, where vertisols were predominant. The highest peak run-off rate of 82.8 m^3/h/ha was recorded at Nemmikal watershed in Nalgonda district. Due to very low seasonal run-off, the soil loss in most of the watersheds was less than 1 t/ha. Only at Nemmikal and Appayapally watersheds was the soil loss higher than 1 t/ha (Table 12.13).

Revolving fund to improve livelihoods

The loans provided through the revolving fund mechanism to the SHGs and to the selected members of various categories of households provided monetary support for undertaking various activities in the villages. In Prakasam district (APRLP, 2006a), the households undertook a number of activities through the revolving fund. The majority of members (51%) have taken up milch cattle units for income generation through selling of milk in the village or nearby areas (Fig. 12.13). At least 8% of members have utilized the loan amount to set up grocery shops, followed by 9% for sheep and goats, and 3% for agricultural purposes. Interestingly, 28% of the members were reported to have invested the amount in miscellaneous activities like tea stalls, cloth shops, STD booths, cable business, tailoring, hotels, etc.

Capacity building

Empowerment of different stakeholders through capacity building in participatory integrated watershed management facilitated the scaling-up of the benefits from the nucleus and satellite watersheds in the target regions (Fig. 12.14).

Sensitization of policy advisors and policy makers

Policy advisors and policy makers are very critical for dissemination and upscaling of the benefits of improved technologies. The principle of ‘seeing is believing’ was adopted, and exposure visits as well as orientation programmes were organized for members of the district capacity-building centres, SHGs, PIAs and farmers, and also for sensitizing the policy makers. Specialized training courses tailored for the farmers, SHGs and youth are needed for enhancing the impacts.

ICT-enabled farmer-centred learning systems for knowledge exchange

It is increasingly realized that facilitation of knowledge flows is key in fostering new rural livelihood opportunities using modern information and communication technologies (ICTs). The concept adapted is one of intelligent

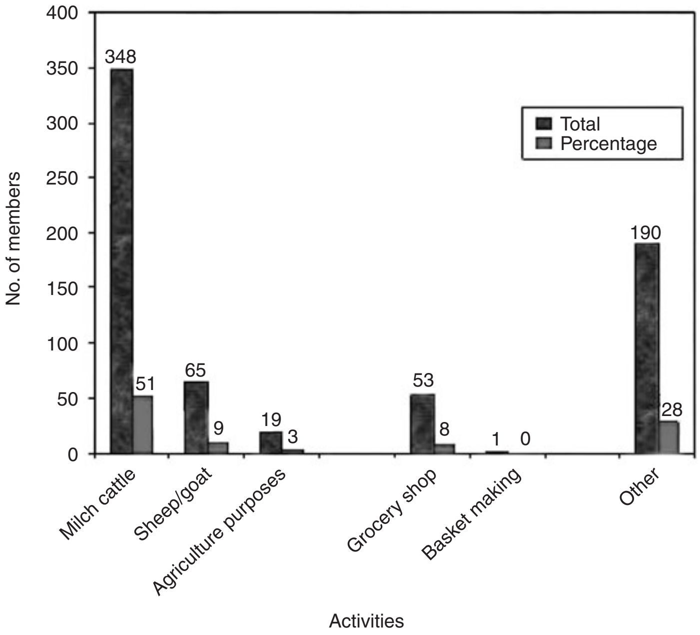


Fig. 12.13. Activities undertaken through the revolving fund in APRLP watersheds in Andhra Pradesh, India.

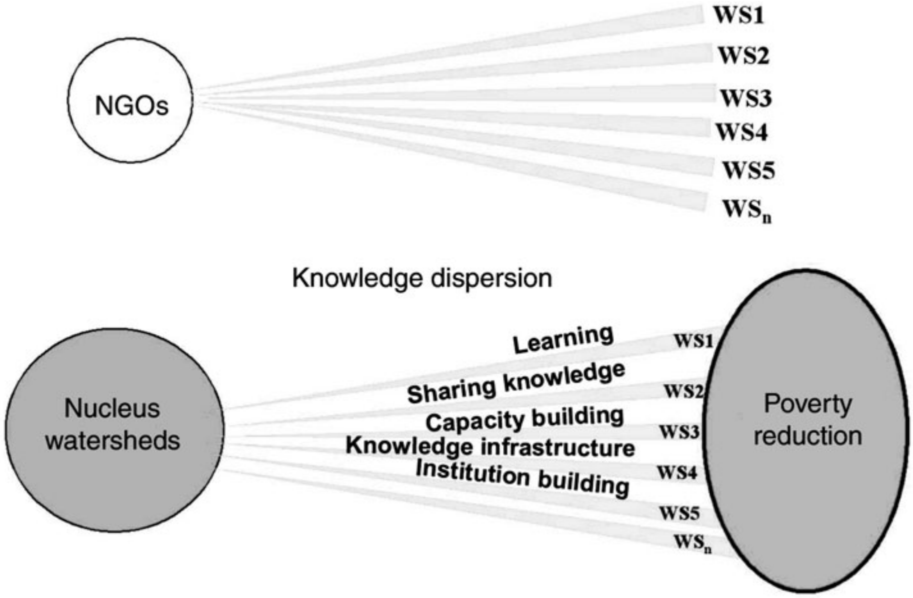


Fig. 12.14. Knowledge transfer within the institution and the region. (WS = watershed)

intermediation for facilitation of flows of information and knowledge. The community centre managed by the PIAs functions as a Rural Information Hub, connecting participating villages (or groups of villages, as the case may be) and also with other internet-connected web sites (Fig. 12.15). It is operated or managed by a rural group (women or youth SHGs) identified by the village watershed council through a consultative process. The activities on this module are planned to adopt a hub-and-spokes model for information dissemination among the participants and stakeholders. The electronic network across select nuclear watersheds enables sharing of experience and best practices.

Other Scaling-out Experiences

The success of the model watersheds of ICRISAT also attracted the Asian Development Bank, Philippines, to upscale the benefits in India, China, north-east Thailand and northern Vietnam. The Sir Dorabji Tata Trust and the Sujala watershed programme in Karnataka, with support from the World Bank, scaled-out the model in the states of Madhya Pradesh, Rajasthan and Karnataka in India to minimize land degradation and improve rural livelihoods through technical backstopping from the ICRISAT-led consortium. Results from the watershed interventions in these locations are very encouraging (Wani *et al.*, 2007).

Improved land, soil and water management practices

Sowing on a BBF landform at Lalatora, Ringnodia (Madhya Pradesh) and Kothapally (Andhra Pradesh) on vertisols and alfisols maintained better moisture conditions, increased infiltration, reduced run-off during the entire crop growth period and increased crop yields (10–40%) through enhanced rainwater use efficiency. At Lalatora watershed the seasonal run-off from the treated watershed was less than one-fifth (55 mm) of that from the untreated watershed (291 mm) (ICRISAT, 2005a). At Tad Fa watershed, Thailand, less than half of seasonal run-off (194 mm) was recorded from the watershed under the improved (fruit trees and seasonal crops) land-use system compared with the watershed with the conventional (seasonal crop) land-use system (473 mm) (ICRISAT, 2006b). Improved watershed technologies were also quite effective in reducing soil loss; the improved technologies recorded a 70% lower seasonal soil loss compared with the untreated watershed at Lalatora. Similarly, at Tad Fa watershed a seasonal soil loss of 15.4 t/ha was recorded from the untreated watershed compared with 10.3 t/ha from the treated watershed (ICRISAT, 2006b), whereas in Karnataka (India) soil loss ranging from 0.7 to 2.0 t/ha was recorded (Table 12.14).

A major impact of improved watershed technologies was seen in improving the groundwater

Fig. 12.15. Information and communication technology services enabled in Mahabubnagar, Andhra Pradesh, India.

Table 12.14. Rainfall, run-off and soil loss at Sujala watersheds in Karnataka, India during 2006[a].

Watershed	Rainfall (mm)	Run-off (mm)	Run-off as % of seasonal rainfall	Peak run-off rate ($m^3/s/ha$)	Soil loss (t/ha)
Haveri (Aremallapur)	350	44	12.6	0.011	2.01
Dharwad (Anchatageri)	652	20	3.1	0.070	1.24
Kolar (Huttur)	547	22	4.0	0.025	0.80
Chitradurga (Toparmalige)	508	16	3.1	0.011	0.66
Mean	514	25.5	5.7	0.029	1.18

[a] Source: ICRISAT (2007).

recharge. Groundwater level rose by 5.75 m in the treated watershed at Lalatora compared with the groundwater level in the untreated watershed. Improvement of marginal lands with appropriate management has resulted in biodiversity improvement, as achieved in Bundi, a very dry watershed in Rajasthan, India (ICRISAT, 2005a).

At Thanh Ha watershed, northern Vietnam, polyethylene and straw mulch increased the soil temperature by 2–3 °C in autumn–winter and 1–2 °C in spring at 10 cm depth, with increased conservation of soil moisture in the entire soil profile (Long *et al*. 2003). Farmers harvested 71–100% increased groundnut yields in the watershed through improved cultivars and integrated soil, water, nutrient and pest management options, and this resulted in doubling the groundnut yield (1.5 t/ha) compared with the control (0.7 t/ha). Farmers in surrounding areas also started adopting this technology (ICRISAT, 2006b).

Introduction of improved crop cultivars and cropping systems

Improved cultivars of soybean, groundnut, wheat, pigeonpea, chickpea, sorghum, pearl millet, maize, vegetables and mung bean were evaluated for large-scale cultivation with improved soil, water and nutrient management options. At Lalatora, the introduction of chickpea varieties ICCV 10, ICCV 2 and ICCC 37 increased production by 4–50% (960–1470 kg/ha) over local varieties. Similarly, in other benchmark watersheds crop productivity increased by 10–50% through adoption of high-yielding cultivars. In Tad Fa watershed of north-east Thailand, maize yield increased by 27–34% over the maize–maize system when preceded by short-duration legumes (black gram, rice bean and sunnhemp). At Thanh Ha watershed, Vietnam, mungbean–groundnut–watermelon, mungbean–soybean–watermelon and groundnut–watermelon cropping systems gave highest income (262–268%) over the traditional maize–maize cropping system. In Rajasthan, short-duration pigeonpea, which is sturdy, drought tolerant and has N-fixing capability, was introduced in three districts and was a great success in the first year alone. About 100 farmers participated in the programme and have harvested up to 1500 kg/ha. Considering the low soil fertility and drought-proneness of the region, this kind of productivity, valued at about INRs 22,000/ha, is a good achievement for the farmers. Improved cultivars and proprietary hybrids of crops with better adaptation to biotic and abiotic stresses and with best practices resulted in more than doubling the crop yields (Table 12.15) in Sujala watershed of Karnataka (ICRISAT, 2007).

Farmers in the Bundi watershed in Rajasthan evaluated IPM options using pheromone traps and *Trichograma* for controlling *Helicoverpa* and *Lepidoptera* pests (ICRISAT, 2005a). They observed that they could reduce inputs by 9% with increased yield of 18% along with 39% higher net economic gain due to adoption of IPM in the case of vegetables. In the watershed

Table 12.15. Farmers' participatory evaluations for productivity enhancements in watersheds of five districts of Karnataka under ICRISAT Sujala project during 2005–2006.

District	Watershed villages	Crop	No. of trials	Cultivars	Yield (kg/ha)	
					FM[a]	Best bet
Kolar & Tumkur	7	Groundnut	63	JL 24, ICGV 91114, K1375, K6	915	2260
Kolar & Tumkur	9	Finger millet	62	MR 1, L 5, GPU 28	1154	1934
Chitradurga	2	Sunflower	30	KBSH-41, KBSH-44, GK 2002	760	2265
Chitradurga & Haveri	4	Maize	49	PA 4642, GK 3014	3450	5870
Haveri	4	Sole groundnut	16	ICGV 91114	1100	1720
Dharwad	4	Soybean	12	JS 335, JS 9305	1350	2470

[a] FM = farmers' management.

areas, farmers have started using 40–45% less chemical pesticides on vegetable cultivation than earlier.

Improved soil and water management and cropping systems (sorghum/pigeonpea intercrop) resulted in higher carbon sequestration in vertisols. Soils up to 120 cm depth contained about 34% more organic carbon than the traditional (fallow–sorghum) system and a gain of 335 kg carbon/ha/year was obtained (Wani *et al*., 2003b). When replicated on a large scale in Asian agriculture, substantial global environmental benefits in terms of reduced greenhouse gases and global warming are likely to be obtained.

Micronutrient amendments for enhancing incomes and rainwater use efficiency

During baseline characterization, soil analysis results showed that 80–100% of farmers' fields were critically deficient in B, Zn and S, in addition to N and P. Micronutrient amendments with Zn, B and S to overcome deficiency have shown remarkable gains. In Thanh Ha watershed, Vietnam, micronutrient application resulted in 27% higher pod yields over farmers' practice (2.75 t/ha) in groundnut. In the Lalatora watershed of India, micronutrient amendments increased the net profit by US$193/ha in the case of the soybean–wheat system over the profit of US$394/ha from the farmers' practice. At Lalatora, Madhya Pradesh, the economic analysis of the on-farm trials showed that intervention of combined application of B and S gave maximum benefit, with 1:1.8 benefit–cost ratio as compared with the control with traditional practices (1:1.3), and gave almost 49% higher benefits to the farmers (Patil *et al*., 2003). Farmers' participatory R&D trials in the states of Andhra Pradesh, Madhya Pradesh, Rajasthan and Gujarat showed 30–60% increased crop yields due to micronutrient amendments (Rego *et al*., 2005). Micronutrient amendments also increased rainfall use efficiency. In soybean, the rainfall use efficiency was increased by 25% through micronutrient amendments. Highest rainfall use efficiency of 117% was observed for sorghum. The rainfall use efficiency in terms of net economic returns for the rainfed crops was substantially higher by 1.5–1.75 times.

Crop harvests from INM trials in Karnataka, India indicate a gain of 2.5 t/ha maize grain yield and 0.5 t/ha additional fodder yield with application of micronutrients along with N and P (Fig. 12.16). In Haveri, farmers obtained 47% higher maize grain yield and in Dharwad 71% higher soybean seed yield with INM treatments compared with their own management (ICRISAT, 2005b).

Micro-enterprises and income-generating activities

Micro-enterprises, such as village seedbanks, vermicomposting, nursery raising, artificial insemination for animals, poultry, piggery, etc., are initiated for increasing income. Village seedbanks have provided access to farmers for improved varieties in the village itself at affordable costs and reduced their dependence on external seed sources. Women SHGs in several watersheds in India have set up vermicompost-

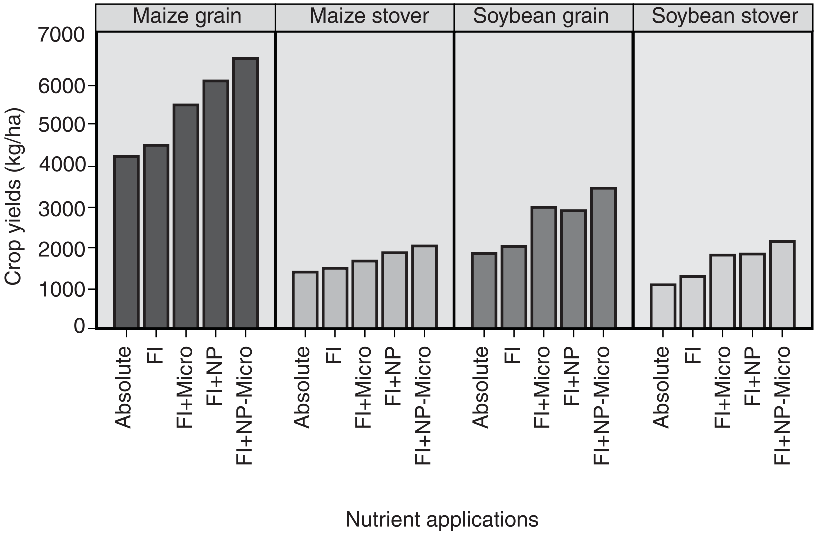


Fig. 12.16. Maize and soybean grain yields as affected by INM treatments in farmers' fields in Sujala watershed in Karnataka. Absolute = control with no fertilizer application; FI = farmers' management and inputs; FI+Micro = farmers' inputs + 5 kg borax + 200 kg gypsum + 50 kg zinc sulfate/ha; FI+NP = farmers' inputs + 70 kg DAP + 100 kg urea; FI+NP+Micro = farmers' inputs + 70 kg DAP + 100 kg urea + 5 kg borax + 200 kg gypsum + 50 kg zinc sulfate/ha (if the crop sown was a legume, application of nitrogen in the form of urea was reduced to 40 kg/ha instead of 100 kg/ha).

ing enterprises. Women members each earn about INRs 500/month. By becoming an earning member of the family, they are involved in the decision-making process, which has raised their social status. Vegetable cultivation, nursery raising and enhanced milk yields through better livestock management have improved rural livelihoods, particularly of women. In Thailand and Vietnam, farmers' incomes are substantially augmented through piggery, poultry and fish rearing.

Impact on National Policy

Integrated watershed management is identified as the most suitable approach to improve the rural livelihoods through increased productivity and efficient management of natural resources in the drylands of the SAT. The National Commission on Farmers (2004), India, has stated that the principal constraints observed in reaping the full benefits from dryland farming research are: (i) lack of a watershed approach with all members of the watershed community working together to save and share water; and (ii) lack of social synergy in the area of land and water use planning, with emphasis on collaborative efforts in both production and postharvest phase of farming. The Commission recommends that the highest priority should be given to augment water availability by vigorously promoting rainwater harvesting, restoring water bodies and a million wells recharge programmes. Convergence and synergy of all agricultural programmes around a watershed is the need of the day. The National Commission on Farmers has appreciated the success of the ICRISAT-led consortium model and pointed out that the holistic innovative model has changed the paradigms for watershed management in India, where the watershed is used as an entry point for improving the livelihoods and protecting the environment. Watershed programmes have a very high potential for bringing favourable changes in the drylands of the SAT. On-farm watersheds managed through community participation could sustain productivity of drylands and preserve the quality of the land resources and environment in the SAT. An holistic systems approach through integrated watershed management can result in sustainable and increased farm productivity and improve the livelihoods of the rural poor in the dry regions (National Commission on Farmers, 2004). The recent Comprehensive Assessment of watershed programmes in India (Wani *et al*., 2008c) and new guidelines for watershed management by the NRAA (Government of India, 2008) clearly highlight the importance of rainfed agriculture for improving rural livelihoods.

Summary

Most farming problems require integrated solutions, with genetic, management-related, and socio-economic components. In essence, plant breeders and NRM scientists must integrate their work with that of private- and public-sector change agents, to develop flexible cropping systems that can respond to rapid changes in market opportunities and climatic conditions. The IGNRM approach is participatory, with farmers closely involved in technology development, testing and dissemination. ICRISAT, in partnership with National Agricultural Research Systems (NARS), has conceived, developed and successfully evaluated an innovative farmers' participatory consortium model for integrated watershed management. The model includes the consortium approach and adopts the concept of convergence in every activity in the watershed.

The new paradigm for upgrading rainfed agriculture can double the productivity in Asia and also reduce poverty without causing further degradation of the natural resource base. Successful scaling-up of these innovations in Andhra Pradesh, India through APRLP and in other states of India with support from the Sir Dorabji Tata Trust and the World Bank (Sujala Project, Karnataka) as well as in Thailand and Vietnam have opened up opportunities to upgrade rainfed agriculture in all these countries as well as in China.

Along with rainwater harvesting and agumentation, water demand management through enhanced water (rainwater and groundwater) use efficiency by adopting a holistic approach has benefited the farmers. Farmers obtained a 13–230% increase in maize yields, with an average increase of 72% over the base yield of 2980 kg/ha; the increase in castor yields was 21–70%, with an average increase of 60% over the base yield of 470 kg/ha. Similarly, groundnut yield increased by 28% over the base yield of 1430 kg/ha. The issues of equity for all in the watershed call for innovative approaches; institution and policy guidelines for equitable use of water resources are needed. Along with water use, equity issues concerning sustainable use of common property resources in the watershed also need to be addressed. Building on micro-enterprises enhanced the benefits for women and vulnerable groups in society. Knowledge management and sharing is an important aspect in management of natural resources for sustainable development. Use of ICTs to cover the last mile to reach the unreached is a must, as the existing extension mechanisms are not able to meet the ever-growing demand, as well as to share the new and vast body of knowledge with the large number of small and marginal farmers.

References

APRLP (Andhra Pradesh Rural Livelihoods Programme) (2006a) *A Study on Utilisation Pattern of Revolving Fund for Enterprise Promotion and Productivity Enhancement in Prakasam District*. APRLP, Government of Andhra Pradesh, India.

APRLP (Andhra Pradesh Rural Livelihoods Programme) (2006b) *Building Livelihoods: the APRLP Experience*. Government of Andhra Pradesh, India.

APRLP (Andhra Pradesh Rural Livelihoods Programme) (2007) *Andhra Pradesh Rural Livelihoods Project: an Overview*. Government of Andhra Pradesh, India.

ASARECA-IFPRI (2005) *Strategic Priorities for Agricultural Research-for-Development in Eastern and Central Africa*. Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA), Entebbe and International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Government of India (2005) *Serving Farmers and Saving Farming – 2006: Year of Agricultural Renewal*. Third Report. December 2005. National Commission on Farmers, Ministry of Agriculture, Government of India, New Delhi, India.

Government of India (2008) Common guidelines for watershed development projects. National Rain-fed Area Authority (NRAA), Ministry of Land Resources, Government of Andhra Pradesh, India.

Gowing, J.W., Mahoo, H., Mzirai, O.B. and Hatibu, N. (1999) Review of rainwater harvesting techniques and evidence for their use in semi-arid Tanzania. *Tanzania Journal of Agriculture Science* 2(2), 171–180.

Harris, H.C., Cooper, P.J.M. and Pala, M. (1991) *Soil and Crop Management for Improved Water Use Efficiency in Rainfed Areas*. Proceedings of an International Workshop sponsored by MAFRA/ICARDA/CIMMYT, 15–19 May 1989, Ankara, Turkey. International Center for Agricultural Research in the Dry Areas (ICARDA), Aleppo, Syria.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2005a) *Combating Land Degradation and Increasing Productivity in Madhya Pradesh and Eastern Rajasthan*. Interim Report 2005. Tata–ICRISAT–ICAR Project, ICRISAT, Patancheru, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2005b) *Establishing Participatory Research-cum-Demonstrations for Enhancing Productivity with Sustainable Use of Natural Resources in Sujala Watersheds of Karnataka*. ICRISAT, Patancheru, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2006a) *Improved Livelihood Opportunities through Watersheds*. APRLP–ICRISAT Project Completion Report (2002–04). ICRISAT, Patancheru, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2006b) *Participatory Watershed Management for Reducing Poverty and Land Degradation in SAT Asia (RETA 6067)*. The Asian Development Bank–ICRISAT Project. TA Completion Report. ICRISAT, Patancheru, India.

ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) (2007) *Establishing Participatory Research-cum-Demonstrations for Enhancing Productivity with Sustainable Use of Natural Resources in Sujala Watersheds of Karnataka – Progress Report*. ICRISAT, Patancheru, India.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. (2005) Meta-analysis to assess impact of watershed program and people's participation. *Comprehensive Assessment Research Report 8*. Comprehensive Assessment Secretariat, International Water Management Institute (IWMI), Colombo, Sri Lanka.

Kerr, J. (1996) Sustainable development of rain-fed agriculture in India. EPTD Discussion Paper No. 20. International Food Policy Research Institute (IFPRI), Washington, DC, USA. (http://www.ifpri.org/divs/eptd/dp/papers/eptdp20.pdf).

Kerr, J., Pangare, G. and Pangare, V. (2002) Watershed development project in India: an evaluation. Research Report No. 127. Environment and Policy Production Technology Division, International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Long, T.D., Ramakrishna, A., Tam, H.M., Viet, N.V. and Chinh, N.T. (2003) Efficient management of natural resources: a way to sustain food security in the rain-fed sloping lands of northern Vietnam. In: Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, TJ. (eds) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 109–122.

Meertens, H., Ndege, L. and Lupeja, P. (1999) The cultivation of rain-fed lowland rice in Sukumaland, Tanzania. *Agricultural Ecosystems Environment* 76, 31–45.

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., Sadoff, C. and Finlayson, M.C. (2007) Trends in water and agricultural development In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 57–89.

National Commission on Farmers (2004) Serving farmers and saving farming. First Report of the National Commission on Farmers. Ministry of Agriculture, Government of India, New Delhi, India.

Patil, B.R., Pande, A.B., Rao, S., Dixit, S.K., Pathak, P., Rego, T.J. and Wani, S.P. (2003) Conjunctive use of water resource technology and extension in improving productivity of rain-fed farming: an experience at Lalatora, Madhya Pradesh, India. In: Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, T.J. (eds) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 97–108.

Rego, T.J., Wani, S.P., Sahrawat, K.L. and Pardhasardhy, G. (2005) Macro-benefits from boron, zinc, and sulphur application in Indian SAT: a step for grey to green revolution in agriculture. *Global Theme on Agroecosystems Report No. 16*. International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Patancheru, India.

Rockström., J., Hatibu, N., Oweis, T. and Wani, S.P. (2007) Managing water in rain-fed agriculture. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in*

Agriculture. Earthscan, London, UK, and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–348.

Sahrawat, K.L., Rego, T.J., Wani, S.P. and Pardhasaradhi, G. (2008) Stretching soil sampling to watershed: evaluation of soil test parameters in a semi-arid tropical watershed. *Communications in Soil Science and Plant Analysis* 39, 2950–2960.

Seckler, D. and Amarasinghe, U. (2004) Major problems in the global water–food nexus. In: Scanes, C. and Miranowski, J. (eds) *Perspectives in World Food and Agriculture 2004*. Iowa State Press/World Food Prize, Ames, Iowa, USA, pp. 227–251.

Shiferaw, B., Freeman, H.A. and Swinton, S. (2004) *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. CAB International, Wallingford, UK.

Shiferaw, B., Bantilan, C. and Wani, S.P. (2006) Policy and institutional issues and impacts of integrated watershed management: experiences and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C. (eds) *Integrated Management of Watersheds for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-Arid South Asia*. Proceedings of the International Workshop held at ICRISAT, Nairobi, Kenya, 6–7 December 2004. International Crops Research Institute for the Semi-arid Tropics (ICRISAT), Patancheru, India, pp. 37–52.

Sreedevi, T.K., Shiferaw, B. and Wani, S.P. (2004) *Adarsha Watershed, Kothapally: Understanding the Drivers of Higher Impact*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Sreedevi, T.K., Wani, S.P., Sudi, R., Patel, M.S., Jayesh, T., Singh, S.N. and Shah, T. (2006) On-site and off-site impact of watershed development: a case study of Rajasamadhiyala, Gujarat, India. *Global Theme on Agroecosystems Report No. 20*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

van Duivenbooden, N., Pala, M., Studer, C., Bielders, C.L. and Beukes, D.J. (2000) Cropping systems and crop complementarity in dryland agriculture to increase soil water use efficiency: a review. *Journal of Agricultural Science* 48, 213–236.

Wani, S.P., Singh, P., Pathak, P. and Rego, T.J. (2000) Sustainable management of land resources for achieving food security in the semi arid tropics. In: Gavande, S.P., Bali, J.S., Das, D.C., Sarkar, T.K., Das, D.K. and Narayanamurthy, G. (eds) *Advances in Land Resources Management for 21st Century*. Angrokor Publishers, New Delhi, India, pp. 290–306.

Wani, S.P., Pathak, P., Tam, H.M., Ramakrishna, A., Singh, P. and Sreedevi, T.K. (2002) Integrated watershed management for minimizing land degradation and sustaining productivity in Asia. In: Adeel, Z. (ed.) *Integrated Land Management in the Dry Areas*. Proceedings of a Joint UNU–CAS International Workshop, 8–13 September 2001, Beijing, China. United Nations University, Tokyo, Japan, pp. 207–230.

Wani, S.P., Maglinao, A.R., Ramakrishna, A. and Rego, T.J. (eds) (2003a) *Integrated Watershed Management for Land and Water Conservation and Sustainable Agricultural Production in Asia*. Proceedings of the ADB–ICRISAT–IWMI Annual Project Review and Planning Meeting, Hanoi, Vietnam, 10–14 December 2001. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Wani, S.P., Pathak, P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003b) Improved management of vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19, 217–222.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003c) Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 199–215.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003d) Farmer participatory integrated watershed management: Adarsha watershed, Kothapally, India – an innovative and upscalable approach. Case 7. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council, Washington, DC, USA, pp. 123–147.

Wani, S.P., Singh, P., Dwivedi, R.S., Navalgund, R.R. and Ramakrishna, A. (2005) Biophysical indicators of agro-ecosystem services and methods for monitoring the impacts of NRM technologies at different scale. In: Shiferaw, B., Freeman, H.A. and Swinton, S.M. (eds) *Natural Resource Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. CAB International, Wallingford, UK, pp. 97–123.

Wani, S.P., Reddy, M., Sreedevi, T.K. and Raju, D. (eds) (2006a) *Corporate Science and Technology Institutions – Partnerships for Inclusive and Sustainable Development and Economic Growth*. Proceedings of the CII–ICRISAT Workshop, 27 February 2006, at ICRISAT. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., Long, T.D., Wangkahart, T., Shiferaw, B., Pathak, P. and Kesava Rao, A.V.R. (2006b) Issues, concepts, approaches and practices in the integrated watershed management: experience and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C (eds) *Integrated Management of Watershed for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-Arid South Asia*. Proceedings of the International Workshop held 6–7 December 2004 at Nairobi, Kenya. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 17–36.

Wani, S.P., Sreedevi, T.K., Rockström, J., Wangkahart, T., Ramakrishna, Y.S., Yin Dxin, Kesava Rao, A.V.R. and Zhong Li (2007) Improved livelihoods and food security through unlocking the potential of rainfed agriculture. In: Aswathanarayana, U. (ed.) *Food and Water Security*. Routledge, UK, pp. 89–106.

Wani, S.P., Joshi, P.K., Raju, K.V., Sreedevi, T.K., Wilson, M., Shah, A., Diwakar, P.G., Palanisami, K., Marimuthu, S., Ramakrishna, Y.S., Meenakshi Sundaram, S.S. and D'Souza, M. (2008a) *Community Watershed as Growth Engine for Development of Dryland Areas – Executive Summary. A Comprehensive Assessment of Watershed Programmes in India*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Wani, S.P., Joshi, P.K., Ramakrishna, Y.S., Sreedevi, T.K., Piara Singh and Pathak, P. (2008b) A new paradigm in watershed management: a must for development of rain-fed areas for inclusive growth. In: Swarup, A., Bhan, S. and Bali, J.S (eds) *Conservation Farming: Enhancing Productivity and Profitability of Rain-fed Areas*. Soil Conservation Society of India, New Delhi, India, pp. 163–178.

Wani, S.P., Sreedevi, T.K. and Marimuthu, S. (2008c) *A Comprehensive Assessment of Watershed Programmes in India*. Proceedings of the Review Meeting and Component Workshops, 23–27 July 2007. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

World Bank (2005) *Agricultural Growth for the Poor: an Agenda for Development*. The International Bank for Reconstruction and Development/The World Bank, Washington, DC, USA.

13 Challenges of Adoption and Adaptation of Land and Water Management Options in Smallholder Agriculture: Synthesis of Lessons and Experiences

B. Shiferaw,[1]* J. Okello[2] and V. Ratna Reddy[3]*****

[1]International Crops Research Institute for the Semi-Arid Tropics, PO Box 36063,
Nairobi 00623, Kenya; [2]Department of Agricultural Economics,
University of Nairobi, PO Box 29053, Nairobi 00625, Kenya;
[3]Centre for Economics and Soil Studies (CESS), Nizamia Observatory Campus,
Begumpet, Hyderabad 500 016, Andhra Pradesh, India;
*emails: *b.shiferaw@cgiar.org; **okelloju@msu.edu; ***vratnareddy@cess.ac.in*

Introduction

Conservation and management of land and water resources for sustainable intensification of agriculture and poverty reduction in many developing regions has remained one of the most challenging policy issues for a long time. The increasing degradation of agroecosystems gradually deprives the poor of key productive resources and affects communities whose livelihoods heavily rely on utilization of these resources. Degradation of land and water resources gradually diminishes the capacity of individual farmers and communities to undertake critical investments needed to reverse the situation. This in turn reduces opportunities for addressing nutritional and other necessities and depletes the ability to buffer shocks, thereby increasing vulnerability of livelihoods. The potential nexus between worsening poverty and degradation of natural resources also raises fundamental questions on strategies for poverty reduction, equitable distribution of income and intergenerational equity. These challenges are highest in many developing regions representing the intersection of hotspots of widespread poverty and fragile ecosystems (e.g. arid and semi-arid areas, highland regions) (Pender and Hazell, 2000; IFAD, 2001; Shiferaw and Bantilan, 2004).

In recognition of these challenges, governments, donors and development partners in many developing countries have devoted substantial resources to develop and promote soil and water conservation practices and technologies for sustainable intensification of agriculture. These technologies are generally very diverse and vary from one region to another but include a mix of indigenous and introduced structural (or mechanical) and agronomic practices for combating soil erosion and nutrient depletion, improving water conservation, and enhancing soil and water productivity. Some examples include structural methods for soil conservation such as soil and stone bunding and terracing; agronomic practices for soil and water conservation and management such as minimum tillage, organic and inorganic fertilizers, grass strips and

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

agroforestry techniques; and water-harvesting options such as tied-ridges, planting basins, check-dams, ponds, tanks and wells used in many rainfed systems (Wani *et al.*, 2006; Chapters 1 and 9, this volume). The structural methods have been promoted through donor-funded projects (e.g. food for work programmes) in many parts of Africa and Asia, primarily for arresting soil erosion and productivity decline. Agronomic methods and agroforestry technologies, in particular alley cropping, aim to reduce soil erosion while also enhancing soil organic matter and have been shown to replenish soil nitrogen through nitrogen inputs. Water-harvesting technologies provide farmers with the opportunity to plant early and help reduce reliance on unpredictable rains (Baidu-Forson, 1999).

Despite the increasing efforts made and the growing policy interest, spontaneous and widespread adoption and adaptation of technologies and innovations for sustainable management of land and water resources by smallholder farmers outside of intensively supported project locations has generally been limited (Fujisaka 1994; Pender and Kerr, 1998; Barrett *et al.*, 2002). Smallholder farmers and resource users continue to face difficulties in adoption and adaptation of soil and water conservation technologies. The diagnosis of these changes and lessons from different examples show that several factors have indeed contributed to the continuing challenges facing smallholder farmers in adoption and adaptation of sustainable land and water management interventions – ranging from the poor performance of the technologies themselves to policy and institutional deficiencies at different levels (Joshi *et al.*, 2005).

In an effort to address these problems, the basic paradigm and approach to soil and water conservation has itself evolved over time. In recent years more holistic and landscape-wide approaches that go beyond resource conservation towards improved land husbandry and water management for beneficial conservation have been promoted (Wani *et al.*, 2006). Taking a broader view, this chapter reviews African and Asian experiences in promoting soil and water conservation and sustainable land management technologies. It synthesizes lessons from various case studies and offers new insights on approaches and strategies that accelerate widespread adoption and adaptation of such interventions.

The chapter is organized as follows. The next section provides a brief description of the evolution of approaches to soil and water conservation in agriculture. The third section provides a broad conceptual framework for analyses of investment opportunities and challenges to smallholder farmers in adoption and adaptation of natural resource management (NRM) interventions. The fourth section builds on the conceptual framework and presents a review of factors that condition the adoption and adaptation of sustainable land and water management interventions. The fifth section presents the conclusions and implications for policy and future research.

Evolution of Approaches for Sustainable Land and Water Management

Concern with land and water degradation in smallholder agriculture is not a new issue. It has been around for a long time and farmers are involved in a constant struggle to adopt and adapt mitigation and conservation strategies under changing climatic and socio-economic conditions. Many countries have also tried to complement farmers' efforts by developing and promoting strategies that reduce the problem of soil erosion (and nutrient depletion) and that counter on-site productivity decline associated with degradation of agricultural land. In some cases, soil erosion and deforestation of hilly slopes also imposed significant off-site effects (e.g. siltation of dams and waterways), thereby adding another justification for government intervention. But the strategies adopted and technological solutions to the problem of land degradation varied over time and space. In many sloping areas with undulating topographies, the traditional emphasis has been on arresting soil erosion and reducing run-off. In semi-arid regions where rainfall is either unreliable or insufficient, the focus has been on technological solutions for capturing and utilizing surface and groundwater.

As indicated above, stimulating widespread adoption and adaptation of land and water management innovations has seen limited success, especially in marginal and vulnerable environments with limited socio-economic infrastructure. In an effort to redress the problem and improve actual livelihood and environmental outcomes, the approach to soil and water conservation has evolved through several phases. These different approaches may be grouped into three major types: top-down interventions, populist or farmer-first, and neo-liberal approaches. Most of the early soil and water conservation approaches focused on top-down interventions, mainly using structural methods for arresting the physical process of soil erosion (Wani *et al.*, 2006). This approach is also characterized by lack of farmer participation in technology design and use of command-and-control type policies for implementation of externally developed structural measures. In the pre-independence era, colonial governments, following concerns with the rapid rate of land degradation in marginal areas (i.e. the reserves), instituted policies that aimed at checking the rate of soil and water degradation. These policies included forced adoption of soil erosion control, planting of trees on hillsides, and protection of water/river catchments. However, the policies were largely driven by fear of future consequences of inaction. Similar top-down approaches also continued in several countries (especially in Africa) until the mid-1980s (e.g. see Shiferaw and Holden, 1998; Pandey, 2001). As we show later, the command-and-control approach has imposed its own challenges on the farmers' ability to innovate and adopt and adapt improved land and water management practices.

Based on the experiences gained from the failed command-and-control policies, a new paradigm – referred to as 'populist' – that upturned the process and made the farmer central to programme design and implementation of soil and water conservation activities has emerged. This view appeared in the late 1980s and was marked by the publication of *Farmer First* – a book that embodies many of the ideas behind the 'populist' approach (Chambers *et al.*, 1989). This approach stressed small-scale and bottom-up participatory interventions, often using indigenous technologies (Reij, 1991) and largely rejected the traditional transfer of technology model in the process of technology development and extension. The difficulties of implementing such farmer-led participatory approaches has prompted some researchers to reject this model in favour of a broader approach, in which farmer innovation is driven by the economic, institutional and policy environment. The neo-liberal approach advocates the need to understand the present structure of incentives that prevents resource users from adopting and adapting existing land and water management technologies. This approach recognizes the appropriate roles for farmer innovation but brings to the centre stage the critical role of markets, policies and institutions to stimulate and induce farmer innovation, adoption and adaptation of suitable options. The critical importance of making conservation attractive and economically rewarding to farmers through productive technologies and improved access to markets is regarded as the driving force for igniting farmer investments in sustainable land and water management options.

The growing understanding and recognition of the public goods characteristics of soil and water conservation and the non-technical factors that condition individual technology choice and adaptation has also prompted strategies that address institutional and organizational constraints and internalize local externalities to induce proper action at the community and landscape level (Shiferaw *et al.*, 2006). An example of this is the integrated watershed management (IWM) approach, which aims to improve both private and communal livelihood benefits from wide-ranging technological and institutional interventions. The concept of IWM goes beyond traditional integrated technical interventions for soil and water conservation to include proper institutional arrangements for collective action and market-related innovations that support and diversify livelihoods. This concept ties together the biophysical notion of a watershed as a hydrological landscape unit with that of community and institutional factors that regulate local demand and determine the viability and sustainability of such interventions. Integration of the biophysical concept of a watershed and the social concept of a community helps to design appropriate technical interventions while also strengthening local institutions for collective action to internalize undesirable externalities and stimulate joint investments to address community-wide resource management problems (Wani *et al.*, 2003, 2006; Shiferaw *et al.*, 2006).

In the last few years, the approach for soil and water conservation in agriculture has also slowly moved towards the concept of sustainable land (and water) management, at both farm and landscape level. There is no single definition for sustainable land (and water) management but Hurni (2000) suggests that it implies ‘a system of technologies and/or planning that aims to integrate ecological and socio-economic and political principles in the management of land for agricultural and other purposes to achieve intra- and inter-generational equity’. The broadening of the concept shows the complexity of the challenges and the need for broadening of desired partnerships and the disciplinary analyses required for stimulating and promoting options for sustainable land and water management. The following section builds on this broader concept of sustainable land (and water) management and develops an integral conceptual framework for analyses of challenges for adoption and adaptation of beneficial conservation methods and practices.

Conceptual Framework

Smallholder farmers in many developing regions are dual economic agents engaging simultaneously in the production and consumption of the same commodities and investments in improving productivity and sustainability of natural resources. Hence, smallholder farmers are often referred to as farm-households. This means that smallholder decisions for land and water management in agriculture are likely to be influenced by several interrelated factors on both the production and consumption side. This is especially the case when smallholder farmers operate under imperfect information and market conditions that prevent them from pursuing a purely profit-maximizing principle in their production and investment decisions. Based on the prevailing approaches discussed above, in this section a broader conceptual framework for analyses of factors that condition farm-household decisions for adoption and adaptation of NRM interventions is presented.

The farm-household, pursuing certain feasible livelihood strategies, is the ultimate decision maker on how and when to utilize natural resources in agricultural production or to undertake certain productivity-enhancing investments to attain preferred objectives. Understanding the investment decisions of the resource users and the most important factors that drive such decisions will allow designing effective strategies for upscaling promising options for sustainable land and water management. In the context of multiple outcomes and pathways that are possible, this would also provide insights on how policy makers, analysts and development practitioners motivate and tailor farmer resource use, production and investment strategies towards win–win pathways that reduce poverty and enhance future production possibilities. This requires a more holistic conceptual framework (as depicted in Fig. 13.1) that captures the intertemporal investment decision problems across alternative livelihood options (crops, livestock and non-farm diversification) and on-farm natural resource investment possibilities that resource users face at each period and the consequences of these livelihood strategies on the quality of the resource base. The pattern of change in the quality of the natural resource base, household assets and livelihoods would then determine the evolution of the ‘development pathway’ and incentives for future natural resource investments in subsequent periods (Shiferaw and Bantilan, 2004).

This conceptual framework builds upon the farmer-first and sustainable livelihoods principle (Chambers, 1987) by incorporating important elements from the theory of farm-household behaviour under market imperfections (de Janvry *et al.*, 1991), the economics of rural organization (Hoff *et al.*, 1993) and the role of economic policies (Heath and Binswanger, 1996), and institutions and institutional change (North, 1990). The conceptual framework clearly recognizes and places household investment decisions in the context of the evolving global, national and local policies and institutional changes that shape production and investment opportunities available to smallholder farmers. This is consistent with the broader evolving interdisciplinary and dynamic perspective required for technology design and development efforts targeting poverty reduction and sustainable NRM in agriculture.

In making their production and investment decisions in each period, smallholder farmers attempt to maximize their livelihood benefits

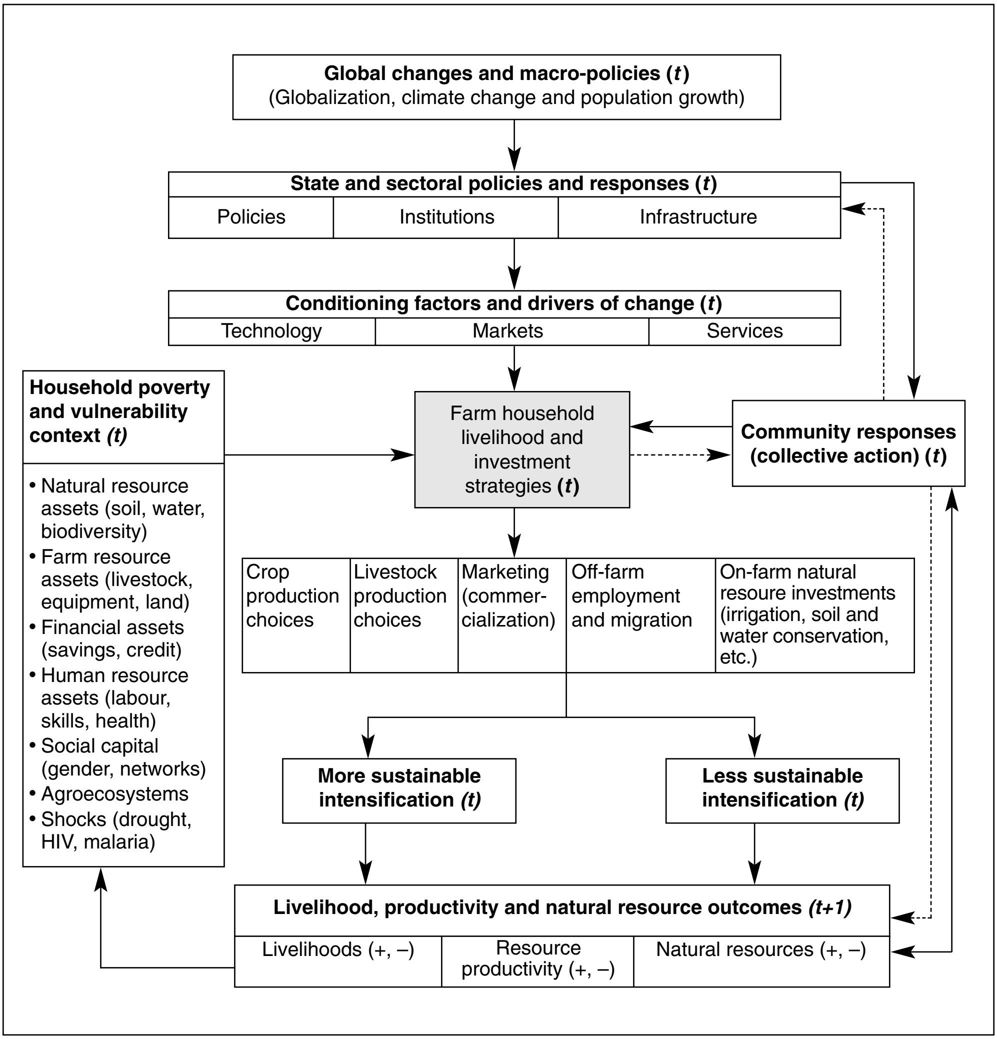


Fig. 13.1. Factors conditioning smallholder natural resource investments and development pathways.

over a period of time based on existing resource assets and expected shocks that jointly determine the vulnerability context. These decisions are also conditioned and mediated by the prevailing socio-economic and policy environment, including subnational and subsectoral policy changes and responses to shifts in global and macro-policies, transmitted to the local level through policy reforms, institutional changes and infrastructural investments, which in turn determine relative input–output prices and access to new technologies and markets at the local level (Shiferaw and Bantilan, 2004). The extent to which global and national policies are transmitted to the local level depends on trade policies and the extent to which input and output markets are integrated. In some situations (e.g. watershed management), collective action by the community may further enhance and supplement individual production and investment possibilities (Sreedevi *et al.*, 2006; Wani *et al.*, 2006).

The diversity of household assets and the prevailing biophysical and socio-economic environment therefore jointly determine the livelihood options and investment strategies available to farmers. Access to markets (including output, credit, input markets), appropriate technologies, and the input and output prices define the production feasibility set and determine the livelihood and investment strategies. While the endowment of family resources and assets determines the initial production and investment capabilities, the socio-economic and policy environment shapes the resource use patterns and the ability to relax initial constraints through trade and market participation (Fig. 13.1).

The framework shows that when more profitable resource-conserving or -improving technologies are available, and capital and institutional constraints are not limiting, farm-households may undertake productivity-enhancing resource investments. Enabling policies (e.g. secure rights to land and water), access to markets and institutional arrangements (e.g. credit services and extension systems) create incentives to invest in options that expand future production and consumption possibilities. Such resource-improving and productivity-enhancing investments provide opportunities for intensification of agriculture and diversification of livelihood strategies that will help combat resource degradation. This will in turn determine the livelihood and natural resource outcomes in the next period ($t+1$). In a dynamic sense, improved level of well-being and natural resource conditions will in turn enhance the stock of livelihood assets available for production, consumption and investment decisions in the subsequent periods. This shows how the interplay of good technology and conducive socio-economic conditions enable some households to pursue a more sustainable intensification strategy that will also help them escape poverty.

Nevertheless, these conditions are often lacking for many smallholder farmers in less-favourable regions with poor market access and suffering from high levels of resource degradation. In the absence of enabling policy and institutional environments that encourage technological innovation, smallholder farmers lack the economic rationale to adopt and adapt interventions for sustainable land and water management. In such situations, increasing subsistence demand and land degradation further undermine the ability to manage the resource base. The interface of lack of viable technological options and adverse biophysical, policy and institutional environments may force smallholder farmers in marginal areas to practise more exploitative and unsustainable livelihood strategies. There may also be several such trajectories leading to less sustainable intensification pathways, indicating extractive resource use patterns (Shiferaw and Bantilan, 2004). In this case, the synergistic effects of poverty and resource degradation lead to worsening conditions of the poor, potentially leading to a downward spiral (Scherr, 2000). Breaking this spiral is a complex challenge requiring innovative strategies that stimulate technical innovation and enabling policy and institutional arrangements, including targeted subsidies for investments, that generate positive public benefits (e.g. poverty reduction and sustainability). Based on a review of examples from Africa and Asia, these specific factors are discussed in the following section.

Determinants of Farmer Conservation Investments

Farmers adopt and adapt new practices and technologies only when the switch from the old to new methods offers additional gains in terms of either higher net returns or lower risks, or both. This means that smallholder farmers are likely to adopt NRM interventions only when the additional benefits from such investments outweigh the added costs (Lee, 2005). Investment in soil and water conservation is often just one of the many investment options available to farmers. Farmers can therefore defer undertaking such conservation investments until the gains from such investments are perceived to be at least equal to the next best investment opportunities available to them (Kerr and Sanghi, 1993). In other words, farmers in developing regions implicitly compare the expected costs and benefits and then invest in options that offer highest net returns (in terms of either income or reduced risk). In some cases, the highest (but short-term) net returns might be realized from foregoing soil and water conservation. Where private costs of adopting and adapting conservation interventions outweigh the benefits, voluntary adoption will be greatly hampered unless society is willing to internalize some of the costs and offer subsidies to farmers.

The literature identifies a number of factors that condition the adoption and adaptation of soil and water management intervention in smallholder agriculture across Asia and Africa. In many cases, farmers reject some interventions for lack of additional benefits (incentive problem). In other cases, farmers also find themselves highly constrained to adopt and adapt otherwise profitable (or economically attractive) interventions due to poverty, imperfect information, market, policy, institutional and other limiting factors. These constraints further limit the economic gains from investments in some NRM interventions and make it unattractive for farmers to adopt and adapt them on their farms. These factors can be broadly categorized into incentive and market factors, poverty and capacity factors, policy and institutional factors, participation and information factors, and environmental factors. These are discussed in turn below.

Markets and incentives

The fundamental economic incentives (related to relative profitability and risk reduction gains) for farmers to adopt NRM interventions are often affected by prevailing relative input and output prices, interest rate, and access to labour and output markets.

Relative output and input prices

Studies that examine the effect of commodity prices on land and water management find mixed effects of price changes on conservation investments. An increase in the price of agricultural commodities may often mask the effect of land degradation and make agricultural production using erosive practices attractive to farmers. In other cases, an increase in commodity prices may make certain NRM interventions profitable or attractive to farmers. Accordingly, some studies find a positive relation between increase in commodity price and adoption of conservation technologies (e.g. Shiferaw and Holden, 2000; Lee, 2005). Shiferaw and Holden (2000) showed that when conservation offers short-term productivity gains, an increase in commodity prices enhances the adoption of soil and water conservation technologies among highland smallholder farmers in Ethiopia. They also found that when conservation does not provide such complementary economic benefits, an increase in the price of an erosive crop would encourage smallholders to expand or intensify the production of such crops without investment in conservation. The same effects can be observed when governments provide price support and other subsidies for certain crops that would distort the incentives faced by resource users. The case in point is the commodity price support to irrigated crops, e.g. rice (*Oryza sativa*) and wheat (*Triticum aestivum*), that discourages farmers in semi-arid areas to cultivate sorghum (*Sorghum bicolor*) and other water-efficient dryland crops. This indicates that policies introduced with good intentions for attaining food security could lead to extensive land degradation and depletion of groundwater resources by encouraging dryland farmers to abandon traditional crops in favour of more erosive or water-intensive irrigated crops (Shiferaw *et al*., 2003). The overall effect of commodity price changes therefore depends on the likely impact of the associated agricultural practice for the particular product and how this affects the relative prices and profitability of conservation investments.

Looking at the input prices, a major determinant of adoption of conservation practices is the price that farmers have to pay to have the technology in place, i.e. the cost of adopting a conservation technology. These costs often raise the cost of production and reduce the profitability of the technology or even make it unaffordable to farmers to invest in such interventions. One obvious example is how an increase in the price of fertilizer may reduce the profitability of its use while also making the input increasingly unaffordable to small producers. This is particularly the case in Africa where countries have removed fertilizer subsidies and poor infrastructure often raises the price of imported fertilizers. As expected, studies that investigate this question find an inverse relationship (Pattanayak and Mercer, 1997). That is, the higher the price of inputs that constitute the conservation practices, the higher the costs and the lower the profitability of the technologies. The majority of these studies investigate how the cost of land and water management interventions (e.g. hedgerow cropping, terracing, minimum tillage, no tillage, etc.) and agricultural water-harvesting techniques affect adoption of such technologies (Pattanayak and Mercer, 1997; Baidu-Forson, 1999). In some cases the cost of conservation may not show directly in terms of actual cash outlays but in terms of indirect short-term effects on production or risk management. But if farmers are able to recognize such indirect costs, they will be factored into their consideration of investment strategies.

Market access and off-farm employment opportunities

Market access for agricultural products often facilitates commercialization of production and adoption of commercial inputs like fertilizer, pesticides and the like. When farmers clearly perceive the future costs of current land degradation and when policy and institutional mechanisms support changes in behaviour, improved market access can be the driving force for sustainable intensification of agriculture. But this is not always the case – there are situations where market access for certain products may end up encouraging less sustainable practices. Hence, the overall effect of improved market access on investments in land and water management is not always positive. The positive role of market access in promoting land and water conservation is best demonstrated by the often-cited example of Machakos district in Kenya (Tiffen *et al*., 1994; Barbier, 2000). The district suffered serious soil erosion problems in the 1930s due to failed colonial government soil conservation policies. By the mid-1980s, the district had not only brought soil erosion largely under control but also realized increased per capita income, even after a sixfold population growth during the period. This tremendous success has been in part attributed to good access to markets for local produce, which was facilitated by proximity to Nairobi. This has accelerated commercialization of agriculture, which raised the profitability of farmer investments, raised incomes and facilitated adoption and maintenance of conservation practices in this largely semi-arid area.

Using large-scale survey data from Uganda, Pender *et al*. (2004) used alternative indicators (physical distance to all-weather road, distance to nearest market, etc.) of market access to examine how these affect crop production and soil erosion. They found that physical distance to the nearest market was not significantly correlated with production or erosion levels, but distance to nearest all-weather road had a negative effect on production and soil erosion.

However, market access is constrained in many rural areas by the poor transport and communication infrastructure, leading to high transaction costs in accessing markets. The associated high transaction costs and limited market opportunities in turn affect adoption of sustainable land and water management options (Pender and Kerr, 1998). Such market failure caused by high transaction costs is especially endemic in marginal areas where basic market infrastructure and supporting institutions are lacking or underdeveloped (Poulton *et al*., 2006). Pender and Kerr (1998), for example, examined the role of output market failure on adoption of soil and water conservation in the semi-arid areas of India. Their findings suggest that market failure in both input and output markets affects the profitability of investments in such technologies and hence constrains adoption. Since market failure often affects households differently depending on their resource endowments, this study explained why technology choice and conservation investments may actually vary from farmer to farmer.

The effect of market access or performance on farmer conservation choice and investments may also vary depending on the dimensions of the affected market. When labour markets are missing or imperfect, the empirical evidence shows that households endowed with more family labour will have an advantage to adopt labour-intensive methods. When credit markets are imperfect, wealthier households with higher liquidity will have an advantage to invest in practices that require cash outlays upfront (Pender and Kerr, 1998).

An interesting relationship is the effect of off-farm and non-farm employment on adoption and adaptation of sustainable land and water management interventions. The empirical findings are mixed (Reardon *et al*., 1994; Pender and Kerr, 1998; Holden *et al*., 2004). In the case of parts of the Ethiopian highlands where on-farm returns to family labour are low, Holden *et al*. (2004) showed that increased availability of opportunities for off-farm employment will have a positive effect on household welfare but a negative tradeoff with reduced soil and water conservation investments. Kerr and Sanghi (1993) found reduced soil and water conservation investments around large Indian cities with active off-farm labour markets compared with more remote areas. Reardon and Vosti (1997) found similar results in their study of adoption of sustainable soil management technologies in Rwanda, Burundi and Burkina Faso. Two reasons are offered in the literature for the negative outcomes. First, under some situations, household workers face higher opportunity costs and prefer to allocate family labour into off-farm activities, where it fetches higher returns than on-farm soil and water conservation. Second, off-farm employment often directly overlaps with slack-season conservation activities and reduces the labour available for adoption and maintenance of conservation practices.

Therefore, opportunities for off-farm employment, when they exist, not only affect the decision to adopt conservation technologies but also the degree of adoption as well as the maintenance of conservation structures once they are in place (Shiferaw and Holden, 2000; Pender *et al.*, 2004). Shiferaw and Holden (2000) found a negative relationship between off-farm income and maintenance of implemented conservation structures. They found that, given the higher returns to off-farm labour, households with unconstrained access to nonfarm employment are likely to conserve less land than their counterparts.

Other authors, however, argue that there exists a positive relationship between off-farm employment and adoption of conservation technologies (Tiffen *et al.*, 1994; Scherr, 2000). These studies review empirical examples across sub-Saharan Africa that show how income from off-farm employment under certain enabling conditions can be used to fund essential soil and water conservation investments and contribute to reducing the problem of land degradation. Off-farm employment and migration opportunities may also ease the pressure on land and reduce the intensity of resource use in densely populated areas.

The emerging picture from the above discussion is that market access, especially off-farm employment, should not necessarily be bad for land and water conservation. It would seem that the direction of the effect will depend on the opportunity cost of labour, the policy and institutional environment, and how important agricultural income is for people's livelihoods. Where returns to family labour in agriculture are high due to better market opportunities and supportive policies that encourage farmer conservation, market access is likely to induce adoption of strategies for sustainable intensification.

Poverty, asset endowments and scarcity

There has been a growing concern about the potential linkages between poverty and land degradation, some positing a nexus that locks poor people under a low-level equilibrium that perpetuates poverty and environmental degradation (Reardon and Vosti, 1995; Holden *et al.*, 1998; Scherr, 2000). Several studies across the developing world have shown that under conditions of imperfect credit and insurance markets, asset endowments and wealth will have a significant influence on the ability of smallholder farmers to adopt and adapt certain conservation practices. This section reviews the empirical regularities and relations between poverty and sustainability investments.

Farmer capacity to invest in conservation

As discussed earlier, credit, insurance and labour markets in rural areas of many developing countries tend to be either missing or highly imperfect. This means that households who lack in cash capital, labour, essential skills or in their ability to manage risks will face constraints, especially when these resources are needed for adoption and adaptation of sustainability investments. This indicates that the smallholder farmer better endowed with such family resources will have greater capacity to undertake certain conservation investments that require more of these resources. For example, education and human capital endowments affect adoption and adaptation of such practices through several directions. First, it enhances the likelihood of farmers perceiving land degradation as a problem. Second, it increases the likelihood of farmers to receive and process information about a technology that can solve the problem by increasing their managerial ability. On the other hand, higher levels of education under certain conditions may raise the opportunity cost of family labour in agriculture and direct its allocation into other activities that offer higher returns (e.g. migration and non-agricultural wage employment).

Another important factor for farmer investment is operating capital or access to credit. This is particularly important for certain capital-intensive investments that require heavy investments upfront (e.g. irrigation, terracing, tree planting and fertilizer use). While credit is generally found to have a significant effect in stimulating farmer investments for land and water management, it may at times conflict with the adoption of indigenous soil and water conservation practices. Holden and Shiferaw (2004) tested the effect of access to input credit (seed and fertilizer inputs) on adoption of sustainable soil and water management strategies in Ethiopia. They observed that increased access to input credit for fertilizer may reduce farmer conservation investments in terms of traditional soil and water conservation works on farmers' fields. This can, however, be tackled through cross-compliance policies that require farmers using subsidized inputs that may cause such tradeoffs to comply with certain minimal on-farm conservation requirements.

Land and water scarcity

The effect of population pressure on incentives for sustainable resource management has been contested for a long time. Diverging theories exist on how population growth and the relative scarcity of agricultural land may affect incentives for land and water management (Boserup, 1965; Cleaver and Schreiber, 1994). These theories will not be reviewed here but empirical evidence provides support to both Malthusian and Boserupian type responses. However, the empirical regularities seem to suggest that, other things being equal, scarcity of land and water would stimulate farmer innovation and investment patterns in conservation practices or methods that augment and enhance the productivity of these resources (Templeton and Scherr, 1999; Scherr, 2000; Mazzucato *et al.*, 2001; Shiferaw and Bantilan, 2004). Lack of proper policy and institutional arrangements and informational asymmetries may, however, prevent farmers from pursuing strategies that save or conserve scarce resources, as is often observed in overexploitation and depletion of common pool resources (groundwater, grazing lands, lake fish, etc.). Similarly, poverty and lack of credit arrangements also prevent farmers from adopting fertilizer and improved seeds, the necessary land-augmenting investments needed as farm size and/or soil fertility decline due to population growth and land degradation.

Risk

Another important factor conditioning adoption and adaptation of conservation technologies is risk. Smallholder farmers are generally risk averse and face constant difficulties in buffering various risks triggered by health, climatic and socio-economic shocks. Hence, land and water management technologies that increase variability or uncertainty of the income stream tend to be shunned by farmers. Such risks can arise from greater odds of crop failure or could be caused by insecure property rights. Whereas soil and water conservation generally tends to reduce production risks, there may be circumstances in which some proposed interventions may actually increase risks (Shiferaw and Holden, 1998; Mazzucato *et al.*, 2001). For example, some water-harvesting technologies can exacerbate flooding problems and cause loss of crop income. A study in Ethiopia found that soil and stone bunds caused pest infestation (or even flooding) that reduced crop yields for farmers (Shiferaw and Holden, 1998), or such technologies may not necessarily increase returns to land and labour in the short term (Shiferaw and Holden, 2001).

In addition to the above risks associated with conservation itself, exogenous risks can also dampen farmers' motivation to adopt conservation technologies. Unless conservation counteracts the problem, the increased risks of crop failure due to weather variability and pest and disease outbreaks can also discourage farmer investments. But substantial empirical evidence shows that when farmers perceive the risk-reducing benefits of conservation investments, they will be willing to increase expenditure as part of their strategy to cope with and adapt to drought and climatic shocks (e.g. water harvesting and irrigation in many semi-arid areas of India and Africa). This shows the need for farmers to recognize the risk-reducing benefits of land and water management interventions, which could serve as an additional incentive to stimulate greater adoption of such practices.

Time preferences

Most resource management investments require heavy initial investments (either in cash or in kind) but deliver benefits many years in the future. At the same time, land and watershed degradation often impose long-term economic and environmental effects. For example, the short on-site productivity effects of soil erosion are often small but impose greater long-term consequences unless action is taken immediately. However, most resource-poor farmers have short planning horizons and face difficulties in adopting a long view (Holden *et al.*, 1998). This is particularly the case when the cost of borrowing is high (e.g. high rates of interest) and capital markets in rural areas are largely imperfect. This raises the subjective rate of discount for poor farmers contemplating certain investments and discourages adoption of technologies that may not offer immediate benefits but improve livelihoods only in the long haul. This is demonstrated in Fig. 13.2.

Let us assume alternative income streams from adoption of different resource management investments (e.g. corresponding to Options 1 to 4 in Fig. 13.2). For simplicity, the current resource-degrading practice is shown under the status quo (Option 1), whereby incomes constantly fall over time. Under the next best available conservation option (Option 2), incomes also decline but more slowly than the current farmer practice. As is typical for many conservation investments, the net income in the first few years to period *t* is lower than the status quo but higher thereafter. The question is whether poor farmers afford to internalize these initial losses in order to gain higher incomes in the future. Evidence shows that if the farmer is just faced with these two alternatives, the resource-conserving available technology (Option 2) is unlikely to be adopted (Holden *et al.*, 1998). The main reason is that poor farmers will find it difficult to sustain initial income losses even when adoption may improve future income to compensate initial losses. Unless subsidized, farmers

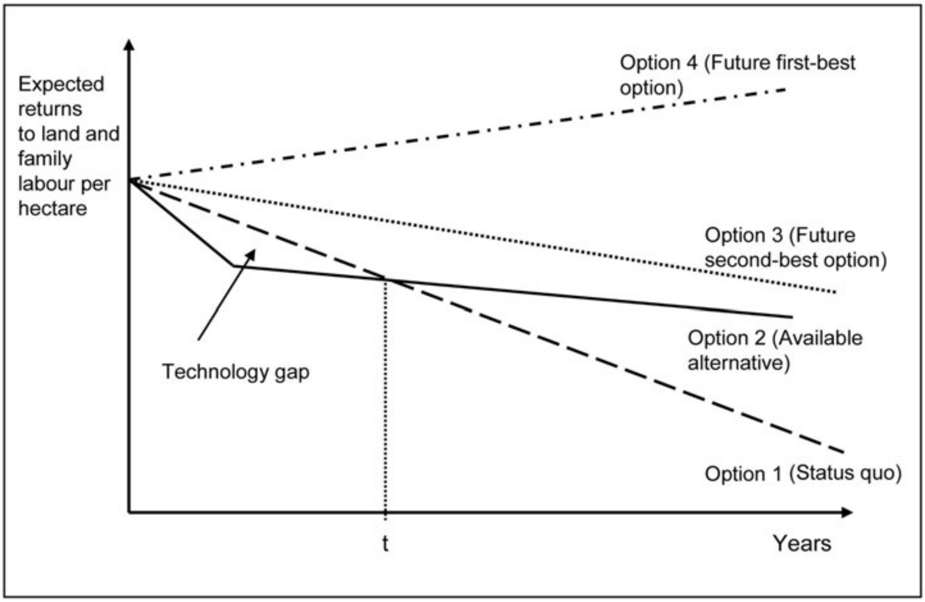


Fig. 13.2. Challenges in the design and development of pro-poor natural resource management technologies.

with a positive discount rate may not be interested in such options.

Alternatively, if the farmers have access to technological options depicted under Options 3 and 4, there will not be such tradeoffs between current and future income. If farmers are not constrained by other factors, one would expect widespread adoption and adaptation of such technologies. One major challenge is that many of the currently available land and water management technologies often cause temporal income tradeoffs and may not be similar to those depicted under Options 3 and 4.

Policy and institutional factors

There has been an increasing recognition of the role that policy and institutions play in sustainable management of natural resources and the environment (Heath and Binswanger, 1996; Barbier, 2000; Pandey, 2001; Reddy, 2005; Shiferaw *et al*., 2006). The effect of markets and prices on adoption of land and water management interventions has been discussed above. In this section, the effects of other agricultural and sector policies and institutions on adoption and adaptation of sustainability investments are examined.

Agricultural policies

One of the important policy issues is the interest of some governments to provide certain agricultural input and investment subsidies to improve productivity and reduce reliance on rainfed agriculture. Unlike some Asian countries (such as India), many African countries have done away with such subsidies, but there is an ongoing debate to reintroduce some targeted subsidies (e.g. for fertilizer, seeds and irrigation). The effect of agricultural policies on conservation investments can best be examined by looking at public support for irrigation water and infrastructure. In India, as in many Asian countries, water for smallholder irrigation is free while the electricity used for pumping groundwater is highly subsidized (Shiferaw *et al*., 2003; Reddy, 2005). These subsidies provide distorted signals to farmers and landholders and displace efforts to invest in soil erosion control and conservation of available water (Shiferaw and Bantilan, 2004; Reddy, 2005). In addition, irrigation subsidies cause farmers to shift cropping patterns to water-intensive crops, which should not be promoted in semi-arid areas. Subsidies can also temporarily raise the returns to conservation practices and create an impression that farmers are investing in the new management practices only for them to resort to old practices once the subsidies are withdrawn. The upshot is that while subsidies could be justified under some conditions where market or institutional failures prevent socially desirable conservation, there is a need for careful appraisal of the equity and sustainability implications of policies that affect smallholder resource use and management decisions.

Institutions for collective action and property rights

The institutional factors conditioning the adoption of conservation technologies mainly relate to the prevailing system of property rights, i.e. the right of access and security of rights to land, water and other natural resources. Understandably, farmers lack economic incentives to invest their time or money if they cannot capture the full benefits of their investments. This condition may prevail when farmers have insecure rights to land (e.g. non-transferable usufruct rights) or when the natural resource is governed by an open access property regime. In addition, farmers are not likely to invest in sustainable resource management of rented private property if the length-of-use right does not allow them to recoup their investments (Ahuja, 1998; Barrett *et al*., 2002; Shiferaw and Bantilan, 2004).

Incomplete property rights and the associated public goods externalities (high costs of exclusion and non-rivalry) can also discourage private conservation investments. This is typical in investments characterized by externalities such as flood control in community watersheds. In some cases the externality may flow in both directions (reciprocal externality) or in one direction. In such cases, the interdependence of resource users and resources (as in watershed programmes) will require collective action and cooperation to achieve socially desirable levels of conservation investments. Promotion of certain interventions that affect several users within a given landscape and provide public goods benefits may therefore require new kinds of policies and institutional arrangements to induce and sustain collective action.

Evidence also shows that collective action (which embodies social capital) can play a significant role in the adoption and adaptation of technologies for conservation and management of contested resources (Wani *et al.*, 2006). Ahuja (1998), Gebremedhin *et al.* (2003) and Pender *et al.* (2004) have examined the effects of collective action (especially membership of a farmer group/association) on adoption of conservation technologies in Côte d'Ivoire, northern Ethiopia and Uganda, respectively. Their results show that collective action can enhance adoption of conservation practices by helping farmers address market failures and information constraints.

The impact of collective action on adoption of land and water management practices is greater when a larger proportion of the community has a shared vision and common interest in maintaining and improving the existing natural resources. Such interests may be similar irrespective of the asset ownership (e.g. landholding) but tend to occur when asset productivities are linked with resource conditions and are influenced by socio-economic and cultural backgrounds of the communities. For instance, evidence from India indicates that the degree of homogeneity in socio-economic and cultural conditions of the community determines the success of community-based lift-irrigation schemes (Deshpande and Reddy, 1990). Other studies have also shown that equity in economic and social structure of the community facilitates collective action (e.g. see Tang, 1992; Bardhan, 1995) because they reduce the transaction costs of mobilizing and organizing the community to undertake joint investments.

Collective action and property rights are also interlinked, although causality is difficult to establish. Property rights can induce and stimulate collective action, especially when property rights guarantee equity in distribution of costs and benefits. In the absence of equitable benefit and cost sharing, strategies that rely on collective action tend to hurt the poor and may not be effective in stimulating adoption and adaptation of conservation technologies. The high transaction costs involved in addressing the equity issues in property rights deter the required changes, thus allowing the persistence of inefficient property rights regimes (Libecap, 2002).

The success of land and water management interventions also depends on the degree to which the user communities are involved through local collective action in the design and implementation of the programmes. In India, studies observe that the programmes implemented by non-governmental organizations often outperform those implemented by the government, mainly because the former ensure active and sustained participation of the community (Vaidyanathan, 1991, 1999; Farrington *et al.*, 1999). Integration of the interests and knowledge of the local community into watershed management programmes also tends to be lacking in government-implemented programmes because government line departments typically centralize the management of such programmes and adopt a top-down bureaucratic approach. In addition, many government-run programmes in the past ignored the importance of integrating other enterprise and economic activities into watershed management programmes and, if they did, it tended to take a top-down uncoordinated approach.

Gender issues

Along with men, women play an important role in improving land and water productivity and conservation of natural resources. In many cases, women are major stakeholders in sustainable NRM, mainly because they represent the main users and immediate direct beneficiaries from improved availability of water, fodder, fuel-wood and other livelihood resources. Successful land and water management interventions that result in increased availability of livelihood resources for domestic use directly benefit women by reducing the time they spend searching for water, fuel-wood and similar resources. While equitable participation of women in land and water management programmes is critical, improvements in resource conditions could release some of the time for investment in land and water management. Available studies also indicate that women often show clear resolve and dedication for resource improvement and tend to be more spiritual in dealing with natural resources, perhaps making them better managers (Mikkelsen, 2005). Integrating the unique interests of women and their active participation at all stages in the process of land and water management can therefore help in improving the effectiveness and sustainability of such interventions (d'Souza, 1998; Pangare, 1998).

The specific needs of women can be addressed more effectively when they participate in decision making and in implementation of the programmes. However, women are often left out of decision making because they rarely own or control resources. In many watershed management projects, women provide hired labour for installation of selected interventions but are not involved in decision making (Sreedevi and Wani, 2007). Pangare (1998), for instance, suggests that women rarely receive the benefits (in terms of access and control) from the resources they help to create and conserve because of social and cultural inhibitions. Future interventions for sustainable land and water management would need to explicitly address the needs of both men and women resource users and seek equitable sharing of benefits (Sreedevi and Wani, 2007).

Information asymmetry and farmer participation

Farmer participation in the design of conservation technologies and availability of information about the potential benefits and risks associated with new methods has an important role to play in influencing farmers' attitudes and perceptions. Many past interventions that followed the top-down non-participatory approach have failed (Reij 1991; Tiffen *et al.*, 1994). A number of factors have contributed to the success of participatory conservation technologies designed using bottom-up approaches. First, such technologies take into account the unique socio-economic characteristics of target farmers, allowing them to adapt to their specific circumstances. Second, farmers are able to test, try or experiment with and adopt various practices at their own pace and preferred sequence. This process of farmer innovation and adaptive experimentation leads to a high degree of compatibility with local situations and farming systems. Third, participatory approaches allow farmers to gradually adapt the technology to changing market and agroclimatic conditions (Bunch, 1989).

The information and perception issues are also important as some types of land degradation may not be directly visible to farmers, especially when external variability in growing conditions makes it difficult for farmers to attribute such changes to declining resource quality. Farmers will adopt technologies only if they perceive soil and water degradation as a major problem that affects their livelihood (Fujisaka, 1994; Baidu-Forson, 1999; Cramb *et al.*, 1999). Along with participatory technology design, education and awareness about new options and the process of resource degradation or depletion (e.g. levels of soil fertility or groundwater depletion) are critical in stimulating awareness and action by individual resource users and communities.

Biophysical environment

Finally, the profitability of natural resource investments will ultimately depend on the agroecological and biophysical conditions. Factors like the natural fertility of soils, topography, climate and the length of the growing period influence the success of research investments and the type of technologies needed to sustain livelihoods and conserve the resource base. For example, meta-analysis of watershed development impacts in India identified rainfall and water availability as major determinants of the success of community watershed programmes. Cost–benefit ratios were found to be largely positive in medium rainfall (701–900 mm) and low-income regions (Joshi *et al.*, 2005). This indicates that in drought-prone semi-arid areas with infertile soils and erratic rainfall patterns, risk considerations imply emphasis on water management to reduce vulnerabilities to drought and to increase crop yields. In such areas suffering from moisture stress and seasonal drought, water conservation provides an important entry point; hence, the need to focus on enhancing *in-situ* conservation and productivity of water. Technologies for water harvesting and supplementary irrigation provide higher incentives for farmers to adopt other complementary inputs. This is mainly because the quick gains in terms of reduced risk of drought and increased productivity of other purchased inputs (e.g. fertilizer) enhance the expected returns from such investments. Similarly, in higher rainfall areas, soil and water conservation may emphasize mitigating soil erosion through cost-effective methods, which reduce overland flow and improve safe drainage of excess water. Even in such areas, the excess water may derive some benefits for supplementary irrigation during the post-rainy season or for domestic and livestock use.

The heterogeneity of the biophysical system in both dry and wet areas therefore suggests the need for careful consideration of local conditions in designing conservation options. The challenge is how to balance applied research needed to adapt to micro-niches with the need for strategic knowledge on cross-cutting issues that will have wider relevance and application.

Conclusions and Policy Implications

This chapter reviewed the challenges that diverse stakeholders and smallholder farmers face in tackling the long-standing problem of land degradation and sustainable management of agroecosystems. Review of the wide literature shows that resource-poor farmers, especially in marginal and rainfed regions, continue to face complex challenges in adopting and adapting alternative management practices and innovations for mitigating this problem. In an effort to address this challenge, the approach to soil and water conservation itself has evolved over several phases, latest perspectives encouraging the need to ensure farmer participation and consideration of market, policy and institutional factors that shape farmers' incentives. The need for farmer participation and innovation is justified by the fact that most soil and water management problems tend to be site and even farm specific. This calls for the need to provide farmers with a set of options to fit specific niches depending on specific constraints rather than a wholesale 'one-size-fits-all' type approach that promotes a single technological package in all areas.

The review also indicates that adoption and adaptation of land and water management innovations is constrained by failure to link conservation with livelihoods, extreme poverty and imperfect factor markets, inadequate property rights systems, and weak organizational and institutional arrangements at different levels. The best way to ensure adoption of innovations for sustainable land and water management is to develop them iteratively, in collaboration with the target group. This can be done through linking formal research with indigenous innovation processes of local resource users and communities. Effective soil and water conservation interventions are characterized by a process of joint innovation that ensures farmer experimentation and adaptation of new technologies and management practices and careful consideration of market, policy and institutional factors that condition and shape farmer conservation decisions.

Linking farmers to better markets for their produce and inputs like fertilizer and credit generally makes a positive contribution in raising the returns to land and labour in agriculture. When complemented with proper policies and institutional mechanisms to induce the process of farmer innovation and adoption of conservation practices, market access can be a useful driving force towards sustainable intensification of smallholder agriculture in both rainfed and irrigated areas. Given that investment poverty and lack of farmer capacity can be a major limiting factor for certain sustainability-enhancing investments, access to investment credit at farmer-affordable rates and availability of pro-poor options for beneficial conservation (i.e. offer short-term livelihood benefits) will be an important step in solving some of the long-standing constraints.

In addition, experience has shown that projects should act as 'toolboxes', giving essential support to resource users to devise complementary solutions based on available options, rather than imposing exogenous practices and technologies. If investments in the resource provide a worthwhile return and when enabling policy and institutional arrangements empower individual resource users and communities, smallholder farmers often try to protect their land and water resources from degradation. The major challenges for future land and water management will be in addressing the externalities and institutional failures that prevent joint investments for management of agricultural landscapes and watersheds. This will require new kinds of institutional mechanisms for empowering communities through local collective action that would ensure broad participation and equitable distributions of the gains from joint conservation investments.

Finally, some of the key lessons for the future include: (i) future land and water conservation projects should be flexible enough to respond to land users' innovations and inputs; (ii) land and water conservation interventions should favour approaches that provide a number of different technologies and management practices, which individual resource users can choose, test, adapt and adopt or discard as they see fit; (iii) resource-poor farmers are unlikely to adopt interventions that do not provide short-term economic gains, especially when credit markets and property rights are imperfect to permit investments with long payback periods; (iv) adoption requires a conducive institutional and policy environment and good linkages with product and factor markets to enhance the returns to beneficial conservation investments; and (v) integrated and landscape-wide interventions require community participation and collective action to coordinate and regulate resource use and investment decisions.

References

Ahuja, A. (1998) Land degradation, agricultural productivity and common property: evidence from Côte d'Ivoire. *Environment and Development* 3, 7–34.

Baidu-Forson, J. (1999) Factors affecting adoption of land-enhancing technology in the Sahel: lessons from a case study in Niger. *Agricultural Economics* 20, 231–239.

Barbier, E. (2000) The economic linkages between rural poverty and land degradation: some evidence from Africa. *Agriculture, Ecosystem and Environment* 82, 355–370.

Bardhan, P. (1995) Rational fools and cooperation in a poor hydraulic economy. In: Basu, K., Pattanaik, P. and Suzumura, K. (eds) *Choice, Welfare and Development: a Festschrift in Honor of Amartya K. Sen*. Clarendon, Oxford, UK, pp. 169–181.

Barrett, C.B., Lynam, J., Place, F., Reardon, T. and Aboud, A.A. (2002) Towards improved natural resource management in African agriculture. In: Barrett, C., Place, F. and Aboud, A. (eds) *Natural Resource Management in African Agriculture: Undersigning and Improving Current Practices*. CAB International, Wallingford, UK, pp. 287–296.

Boserup, E. (1965) *The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure*. Earthscan Publications Ltd, London, UK.

Bunch, R. (1989) Encouraging farmer's experiments. In: Chambers, R., Pacey, A. and Thrupp, L. (eds) *Farmer First: Farmer Innovation and Agricultural Research*. Intermediate Technology Publications, London, pp. 55–59.

Chambers, R. (1987) Sustainable livelihoods, environment and development: putting poor people first. Discussion Paper 240. Institute of Development Studies, University of Sussex, Brighton, UK.

Chambers, R., Pacey, A. and Thrupp, L. (eds) (1989) *Farmer First: Farmer Innovation and Agricultural Research*. Intermediate Technology Publications, London.

Cleaver, K.M. and Schreiber, G.A. (1994) *Reversing the Spiral: The Population, Agriculture and Environmental Nexus in sub-Saharan Africa*. The World Bank, Washington, DC, USA.

Cramb, R.A., Garcia, J.N.M., Gerrits, R.V. and Saguiguit, G.C. (1999) Smallholder adoption of soil conservation technologies: evidence from upland project from the Philippines. *Land Degradation and Development* 10, 405–423.

de Janvry, A., Fafchamps, M. and Sadoulet, E. (1991) Peasant household behaviour with missing markets: some paradoxes explained. *Economic Journal* 101, 1400–1417.

Deshpande, R.S. and Reddy, V.R. (1990) Social dynamics and farmer's society: a case study of Pani-Panchayat. *Indian Journal of Agricultural Economics* 45, 355–361.

d'Souza, M. (1998) Watershed development – creating space for women. Agricultural Research & Extension Network Paper No. 88b, ODI, London, pp. 10–20.

Farrington, J., Turton, C. and James, A.J. (eds) (1999) *Participatory Watershed Development: Challenges for the Twenty-first Century*. Oxford University Press, New Delhi, India.

Fujisaka, S. (1994) Learning from six reasons why farmers do not adopt innovations intended to improve sustainability of upland agriculture. *Agricultural Systems* 46, 409–425.

Gebremedhin, B., Pender, J. and Tesfay, G. (2003) Community natural resource management: the case of community woodlots in northern Ethiopia. *Environment and Development Economics* 8, 129–148.

Heath, J. and Binswanger, H.P. (1996) Natural resource degradation effects of poverty and population growth are largely policy induced: the case of Colombia. *Environment and Development Economics* 1, 64–84.

Hoff, K., Braverman, A. and Stiglitz, J.E. (eds) (1993) *The Economics of Rural Organisation*. Oxford University Press, New York.

Holden, S. and Shiferaw, B. (2004) Land degradation, drought and food security in the less-favoured areas of Ethiopian highlands: a bio-economic model with market imperfections. *Agricultural Economics* 30, 31–49.

Holden, S.T., Shiferaw, B. and Wik, M. (1998) Poverty, credit constraints, and time preferences: of relevance for environmental policy? *Environment and Development Economics* 3, 105–130.

Holden, S., Shiferaw, B. and Pender, J. (2004) Non-farm income, household welfare and sustainable land management in the less favoured area in the Ethiopian highlands. *Food Policy* 29, 369–392.

Hurni, H. (2000) Assessing sustainable land management (SLM). A*griculture, Ecosystems and Environment* 81, 83–92.

IFAD (2001) *Rural Poverty Report. The Challenge of Ending Rural Poverty*. Oxford University Press and the International Fund for Agricultural Development (IFAD), Rome, Italy.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. (2005). Meta-analysis to assess impact of watershed programme and people's participation. Research Report No.8. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Kerr, J. and Sanghi, N. (1993) Indigenous soil and water conservation in India's semi-arid tropics. Gatekeeper Series No. 34. International Institute for Environment and Development, London, UK.

Lee, D.R. (2005) Agricultural sustainability and technology adoption in developing countries: issues and policies for developing countries. *American Journal of Agricultural Economics* 87, 1325–1334.

Libecap, G.D. (2002) A transaction costs approach to the analysis of property rights. In: Brousswau, E. and Glachant, J.M. (eds) *The Economics of Contracts: Theory and Applications*. Cambridge University Press, Cambridge, UK, pp. 140–156.

Mazzucato, V., Niemeijer, D., Stroosnijder, L. and Rolling, N. (2001) Social networks and the dynamics of soil water conservation in Sahel. Gatekeeper Series SA101. International Institute for Environment and Development, London, UK.

Mikkelsen, C. (2005) Indigenous peoples, gender and natural resource management. Working Paper No. 2005/5. Danish Institute for International Development, Copenhagen, Denmark.

North, D.C. (1990) *Institutions, Institutional Change and Economic Performance*. Cambridge University Press, Cambridge, UK.

Pandey, S. (2001) Adoption of soil conservation practices in developing countries: policy and institutional factors. In: Bridges, E., Hannam, I., Oldeman, I., Penning de Vries, L., Scherr, F. and Sombatpanit, S. (eds) *Response to Land Degradation*. Science Publishers Inc., Enfield, New Hampshire, USA, pp. 66–73.

Pangare, P.L. (1998) Gender issues in watershed development and management in India. In: *Agricultural Research & Extension Network Paper No. 88a*, pp. 1–9.

Pattanayak, S. and Mercer, D.E. (1997) Valuing soil conservation benefits of agroforestry: contour hedgerows in eastern Visayas, Philippines. *Agricultural Economics* 18, 31–46.

Pender, J. and Hazell, P. (2000) Promoting sustainable development in less-favoured lands: overview. In: Pender, J. and Hazell, P. (eds) *Promoting Sustainable Development in Less-favoured Lands*. Focus 4. IFPRI, Washington, DC, p. 2.

Pender, J.L. and Kerr, J.M. (1998) Determinants of farmers' indigenous soil and water conservation investments in semi-arid India. *Agricultural Economics* 19, 113–125.

Pender, J.L., Nkonya, E., Jager, P., Serunkuuma, D. and Ssali, H. (2004) Strategies to increase agricultural productivity and reduce land degradation. *Agricultural Economics* 31, 181–195.

Poulton, C., Kydd, J. and Dorward, A. (2006) Overcoming market constraints on pro-poor agricultural growth in sub-Saharan Africa. *Development Policy Review* 24, 243–277.

Reardon, T. and Vosti, S.A. (1995) Links between rural poverty and environment in developing countries: asset categories and investment poverty. *World Development* 23, 1495–1503.

Reardon, T. and Vosti, S.A. (1997) Poverty environment links in rural areas of developing countries. In: Vosti, S.A. and Reardon, T. (eds) *Sustainability, Growth, and Poverty Alleviation: a Policy and Agroecological Perspective*. The Johns Hopkins University Press.

Reardon, T., Crawford, E. and Kelly, V. (1994) Links between non-farm income and farm investments in African households: adding capital market perspective. *American Journal of Agricultural Economics* 76, 1172–1176.

Reddy, V.R. (2005) Costs of resource depletion externalities: a study of groundwater overexploitation in Andhra Pradesh, India. *Environment and Development Economics* 10, 533–556.

Reij, C. (1991) Indigenous soil and water conservation in Africa. Gatekeeper Series 27. International Institute for Environment and Development, London, UK.

Scherr, S. (2000) A downward spiral? Research evidence on the relationship between poverty and natural resource degradation. *Food Policy* 25, 479–498.

Shiferaw, B. and Bantilan, C. (2004) Rural poverty and natural resource management in less-favoured areas: revisiting challenges and conceptual issues. *Journal of Food, Agriculture and Environment* 2(1), 328–339.

Shiferaw, B. and Holden, S.T. (1998) Resource degradation and adoption of land conservation technologies in the Ethiopian highlands: a case study in Andit Tid, North Shewa. *Agricultural Economics* 18(3), 233–248.

Shiferaw, B. and Holden, S. (2000) Policy instruments for sustainable land management: the case of highland smallholders in Ethiopia. *Agricultural Economics* 22, 217–232.

Shiferaw, B. and Holden, S. (2001) Farm-level benefits to investment for mitigating land degradation. *Environment and Development Economics* 6, 355–358.

Shiferaw, B., Wani, S.P. and Nageswara Rao, G.D. (2003) Irrigation investments and groundwater depletion in Indian semi-arid villages: the effect of alternative water pricing strategies. Working Paper No. 17. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Shiferaw, B., Bantilan, C. and Wani, S.P. (2006) Policy and institutional issues and impacts of integrated watershed management: experience and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C (eds) *Integrated Management of Watersheds for Agricultural Diversification and Sustainable Livelihoods: Lessons and Experiences from Semi-arid South Asia.* International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 37–52.

Sreedevi, T.K. and Wani, S.P. (2007) Leveraging institutions for enhanced collective action in community watersheds through harnessing gender power for sustainable development. In: Mudrakartha, S. (ed.) *Empowering the Poor in the Era of Knowledge Economy.* Confederation of NGOs in the Rural India, New Delhi, India, pp. 27–39.

Sreedevi, T.K, Wani, S.P., Sudi, R., Patel, M.S., Jayesh, T., Singh, S.N. and Shah, T. (2006) On-site and off-site impact of watershed development: a case study of Rajasamadhiyala, Gujarat, India. *Global Theme on Agroecosystems Report No. 20.* International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Tang, S.Y. (1992) *Institutions and Collective Action: Self-governance in Irrigation.* Institute for Contemporary Studies, San Francisco, California, USA.

Templeton, S.R. and Scherr, S.R. (1999) Effects of demographic and related microeconomic change on land quality in hills and mountains of developing countries. *World Development* 27, 903–918.

Tiffen, M., Martimore, M. and Gichuki, F. (1994) *More People Less Erosion: Environmental Recovery in Kenya.* John Wiley and Sons, London, UK.

Vaidyanathan, A. (1991) Integrated watershed development: some major issues. Foundation Day Lecture, Society for Promotion of Wasteland Development, New Delhi, India.

Vaidyanathan, A. (1999) *Water Resource Management: Institutions and Irrigation Development in India.* Oxford University Press, New Delhi, India.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003) Farmer participatory integrated watershed management: Adarsha watershed, Kothapally, India. An innovative and upscalable approach. Case 7. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR.* Interim Science Council, Consultative Group on International Agricultural Research, Washington, DC, USA, pp. 123–147.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., Long, T.D., Wangkahart, T., Shiferaw, B., Pathak, P. and Kesava Rao, A.V.R. (2006) Issues, concepts, approaches and practices in the integrated watershed management: experience and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C (eds) *Integrated Management of Watershed for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-arid South Asia.* Proceedings of the International Workshop held at ICRISAT, Nairobi, Kenya, 6–7 December 2004. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 17–36.

14 Scaling-out Community Watershed Management for Multiple Benefits in Rainfed Areas

P.K. Joshi,[1]* A.K. Jha,[1] S.P. Wani[2]*** and T.K. Sreedevi[2]******
[1]National Centre for Agricultural Economics and Policy Research, New Delhi 110 012, India; [2]International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India;
*emails: *pkjoshi@ncap.res.in; **akjha@ncap.res.in; ***s.wani@cgiar.org; ****t.sreedevi@cgiar.org*

Introduction

Low productivity in rainfed areas, aggravated by water scarcity, degraded and poorly managed land, poor infrastructure and lack of market, marginalizes agriculture and livelihoods in the rainfed areas. Demographic pressures in developing countries of Asia and Africa and increased vulnerability due to changing climate have further exacerbated the sustainability and threatened livelihoods in rainfed areas. Globally 80% of agriculture is rainfed; in South Asia it is about 60–65%; and in sub-Saharan Africa it varies between 90 and 95% (Rockström *et al.*, 2007). About 66% of total arable land (142 million ha) in India is rainfed and suffers acute moisture stress. Although the green revolution helped Asia, particularly India, to attain self-sufficiency in food production, it bypassed millions of poor living in rainfed areas. None the less, in so-called green revolution areas signs of yield fatigue and unsustainability are evident (Pingali and Raney, 2005). Water is a critical constraint to increasing agricultural productivity. It is estimated that by 2025, one-third of the population in developing countries, including 50% of the population of India and China, will be facing physical scarcity of water. The recent Comprehensive Assessment of Water for Food and Water for Life showed that challenges of poverty and food security with looming water scarcity cannot be met by irrigated agriculture alone, and major gains have to come through upgrading rainfed agriculture (Molden *et al.*, 2007). In India, even after exploitation of the full irrigation potential, about 60% of the arable area will continue to depend on rainfed farming. Both surface and groundwater resources are under considerable pressure and have depleted considerably. Falling groundwater tables, due to excessive exploitation and low recharge, have led to disastrous consequences. The Central Groundwater Board of India has identified 100 ‘critical’ districts in the country where excessive use of groundwater has led to serious economic and sustainability problems and 85 of these districts are situated in rainfed regions. Estimates of water availability vis-á-vis requirement in 2050 indicate a yawning gap between demand and supply. Projections of water requirement show that in 2050 the country’s utilizable water availability of 1122 km^3/year will hardly be able to match the estimated requirement of 1450 km^3/year (Gupta and Deshpande, 2004). The agriculture sector is the single largest user of

Rainfed Agriculture: Unlocking the Potential (eds S.P. Wani *et al.*)

water, which accounts for more than 80% of the total present demand. Estimates show that about 68% of the total water requirement (i.e. 628–807 km^3/year) would be available for the irrigation sector in 2050 (Sharma, 2002). It indicates an alarming situation in the years to come. If the present trend continues, water availability will reach the stress level of 1700 m^3/person by 2025 and the scarcity level of 1236 m^3/person in 2050 (Sharma, 2002). In most rainfed areas, water availability is not a problem but rainfall distribution and poor management creates water scarcity for crops, resulting in low rainwater use efficiency (40–45%) and low crop production (Wani *et al.*, 2003a). Rainwater stored in soil largely escapes to atmosphere through unproductive evaporation, and large water productivity gains could be achieved in rainfed areas by changing vapour flows through productive evapotranspiration (green water) (Rockström *et al.*, 2007).

This is a matter of concern and requires developing appropriate strategies that ensure augmentation of water resources through all possible measures, including rainwater conservation and harvesting as well as efficient and economical use of water in rainfed areas. Development of watersheds/catchments is one of the most trusted and eco-friendly approaches to manage rainwater and other natural resources, which has paid rich dividends in the rainfed areas and is capable of addressing many natural, social and environmental intricacies (Samra, 1998; Wani *et al.*, 2002, 2003b,c; Rockström *et al.*, 2007; Chapter 2, this volume). Management of natural resources at catchment/watershed scale produces multiple benefits in terms of increasing food production, improving livelihoods, protecting the environment and addressing gender and equity issues along with biodiversity concerns (Wani *et al.*, 2003b,c; Rockström *et al.*, 2007). Watershed development programmes (WDPs) are therefore considered as a growth engine for development of fragile and marginal rainfed areas (Wani *et al.*, 2008a).

This chapter assesses the ways and means of enhancing the benefits of watershed programmes through scaling-out strategies by identifying biophysical and socio-economic drivers of success based on critical analysis of case studies. It also identifies conditions for larger participation of the stakeholders in the watershed activities, which is a prerequisite for successful implementation and sustainability of the watershed development projects. To face the challenges of reducing poverty and thus meet the target of halving the number of poor in the world and also to build resilience to the impacts of climate change, a strategy for upgrading rainfed agriculture in developing countries is discussed.

Watershed Development Programme in India

In the tropics, rainfall is erratic and not well distributed during the season, resulting in long dry spells as well as severe run-off and soil erosion during the crop growing period. Year-to-year variation in rainfall as well as its distribution during the season is quite large. In 2007, Kurnool town in Andhra Pradesh received 420 mm rainfall in 24 h as against the long-term monthly average of 77 mm. Similarly, Adarsha watershed in Kothapally in Rangareddy district in Andhra Pradesh received 346 mm rainfall in 24 h on 24 August 2000 as against annual average of 800 mm. In 2006, Rajasthan, which normally suffers from deficient rainfall, experienced unusual floods in the districts, causing severe losses of humans and livestock, in addition to the huge financial losses. Ten rivers, overflowing and flooding Pali, Sirohi, Udaipur, Banswara, Jhalawar, Dungarpur, Kota and Chittorgarh districts in Rajasthan, caused enormous losses, including the death of 138 people and a large number of livestock. The most affected area was Barmer, in the Thar desert, where the houses remained flooded under 6 m of water. Barmer received about 577 mm of rainfall, 300 mm more than the annual average rainfall of 277 mm. To manage such extreme situations of water scarcity and excess, watershed development in rainfed areas provides a suitable solution to these problems (Chapter 1, this volume).

The most important feature of watershed development is *in-situ* conservation and harvesting rainwater for augmenting surface and groundwater resources in rainfed areas. Watershed development aims at optimum and prudent use of soil and water resources in a sustainable and cost-effective mode.

Augmentation of water resources is at the heart of WDPs.

The catchment watershed development approach is a viable option for unlocking the potential of rainfed areas and doubling or quadrupling the productivity through augmenting water resources in the rainfed areas (Rockström *et al.*, 2007; Wani *et al.*, 2007). Watershed management is of strategic importance in bringing in the 'second green revolution' and achieving the goal of 4% agricultural growth in the country. Evidence shows that the watershed approach to rainfed farming with water harvesting and supplemental irrigation technologies shows great promise for increasing groundwater recharge and crop yields since the seventh 5-year plan (Sharma, 2002; Wani *et al.*, 2003b,c; Joshi *et al.*, 2005). The government of India, therefore, has accorded high priority to the holistic and sustainable development of rainfed areas through the integrated watershed development programme (Wani *et al.*, 2008a).

The emphasis is on the augmentation of water resources by implementing small watershed projects. The majority of watershed development projects in the country are sponsored and implemented by the government of India with the help of various state departments, non-governmental organizations (NGOs), self-help groups (SHGs), etc. The Drought-Prone Area Programme (DPAP), the Desert Development Programme (DDP), the National Watershed Development Project for Rainfed Area (NWDPRA), the Watershed Development in Shifting Cultivation Areas (WDSCA) and the Integrated Watershed Development Project (IWDP) are a few of the important development programmes that plan, fund and implement watershed development projects. A total sum of US$7 billion has been invested in the country in various watershed development projects from the inception (early 1980s) of WDPs until 2006. Several international organizations, including the Department for International Development (DFID), the Deutsche Gesellschaft for Technische Zusammenarbeit (GTZ), the Swiss Agency for Development and Cooperation (SDC), the World Bank, and the International Fund for Agricultural Development (IFAD), also sponsor and implement watershed development projects, but a significant proportion (about 70%) of the investment in WDPs is being made by the government of India. Evidence shows that WDPs have yielded considerable benefits in terms of increasing agricultural productivity, groundwater recharge, reducing run-off and soil loss, increasing greenery, diversifying cropping systems, conserving biodiversity, equity, sustainability and efficiency (Farrington and Lobo, 1997; Hanumantha Rao, 2000; Kerr *et al.*, 2000; Joshi *et al.*, 2003, 2005; Wani *et al.*, 2003b,c).

Approach

The watershed development approach in India has evolved over time, based on the knowledge gained from various programmes. Wani *et al.* (2006a) noted that it started with soil and water conservation programmes and then laid emphasis on water harvesting and increasing crop productivity and recently focused on full livelihood improvement programmes. Although new approaches such as livelihood improvement and productivity enhancement are developed and have proven their superiority, large numbers of watershed programmes have not graduated fully into holistic/integrated programmes. Most programmes heavily emphasized water augmentation interventions but did not accord much emphasis on efficient use of conserved soil and water resources (Wani and Ramakrishna, 2005). Similarly, many watershed programmes did not address the issues of women and vulnerable groups, and in the process they paid the price of development with increased workload without any tangible social or economic benefits to women (Meinzen-Dick *et al.*, 2004; Shah, 2007; Sreedevi and Wani, 2007).

Along with the evolution of the compartmental approach to the integrated and holistic approach, the processes and institutional arrangements also evolved. The government of India responded with revision of watershed guidelines, emphasizing more collective action and participation by the primary stakeholders (Government of India, 1994; Hanumantha Rao, 2000) and involvement of community-based organizations (CBOs), NGOs and Panchayat Raj Institutions (DOLR, 2003). For ensuring tangible economic benefits to individual farmers, women and vulnerable group members, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has developed an effective consortium approach for integrated watershed development (Wani *et al.*, 2003c), and the approach is used for upscaling in India and other Asian countries (China, Vietnam, Thailand and Philippines) (Wani *et al.*, 2006a). The public–private partnerships (PPP) in the area of integrated watershed development and management are emerging (Wani *et al.*, 2007a) and are also encouraged by the Government of India (2005).

To identify biophysical, socio-economic and institutional drivers, a number of watershed case studies have been analysed. For monitoring the impact of watershed programmes on various aspects, appropriate indicators are being evaluated (Joshi *et al.*, 2004; Pathak *et al.*, 2004; Shiferaw *et al.*, 2006; Wani *et al.*, 2006a; Shah, 2007). The various biophysical and socio-economic indicators used for assessing the macro- and micro-level impacts of watershed programmes are listed in Table 14.1. At the macro level, the aggregate impacts of watershed programmes in India were assessed by Joshi *et al.* (2003, 2005), considering different socio-economic and agroecological indicators by adopting a meta-analysis approach. At the micro level, a number of detailed case studies (Wani *et al.*, 2003a; Sreedevi *et al.*, 2004, 2006; Shiferaw *et al.*, 2006) were evaluated and analysed to observe the micro-level impacts of different watershed programmes in the country.

Benefits of watershed programmes

The watershed programmes produce multiple tangible and intangible benefits for individuals as well as for communities as a whole. The present generation watershed programmes are not only conserving but also augmenting water and land resources, increasing agricultural and livestock productivity, enhancing incomes, protecting and providing environmental services, promoting collective action and addressing issues of women and equity for vulnerable groups through development of social capital and institutions, including building resilience of natural and human resources to cope with future changes, including those due to climate change (Wani *et al.*, 2008b). Therefore, watershed management has been a key component of development planning of rainfed drought-prone areas since the early 1980s.

The results of meta-analyses using 311 case studies showed that watershed programmes, apart from raising income levels and generating employment opportunities, have been remarkably successful in conserving and augmenting water resources in the rainfed areas, by the adoption of different soil and water conservation measures and trapping of surface run-off water. A summary of multiple benefits derived from watersheds, as indicated in various studies, is shown in Table 14.2. It is obvious that watershed programmes in India have yielded multiple exemplary benefits, including augmentation of water resources. The watershed programmes are largely aimed at conserving soil and water to raise farm productivity. The available evidence revealed that both these objectives were accomplished in the watershed areas. Conserving soil means raising farm productivity and transferring good soils to the next generation. It was noted that, on average, about 38 ha-m additional water storage capacity was created as a result of the watershed programme in 500-ha watersheds. Augmenting water-storage capacity contributed to: (i) reducing rate of run-off; and (ii) increasing groundwater recharge. This has a direct impact in expanding the irrigated area and increasing cropping intensity. On average, the irrigated area increased by about 34%, while the cropping intensity increased by 64%. Such an impressive increase in the cropping intensity was not realized in many surface-irrigated areas in the country (Joshi *et al.*, 2005).

However, it is important that unless a programme is economically viable, it will never succeed. Fortunately, the mean benefit– cost ratio of the watershed programme was also quite modest at 2.14 (Table 14.2). This revealed that investment in the watershed programmes under fragile and challenging rainfed environments has yielded enormous benefits (more than double). About 15% of watersheds attained a benefit–cost ratio of more than three (Fig. 14.1). Only less than 3% of the watersheds were reported to have a benefit–cost ratio of less than one. The mean internal rate of return on watershed investment was about 22%, with a maximum of 94% (Joshi *et al.*, 2005).

Table 14.1. Agricultural sustainability criteria and indicators.

Criteria	Indicators
Agrodiversity	Index of surface percentage of crops (ISPC)
	Crop agrobiodiversity factor (CAF)
	Genetic variability
	Surface variability (monoculture)
Agrosystem efficiency	Yield and yield gap
	Cost–benefit ratio
	Parity index
Use of the land resource base	Land availability/land demand
	Land demand/land used
	Cultivated land/inhabited
	Cultivated land/deforested land
	Irrigated land/irrigable land
	Degraded land
Food security	Per capita production index
	Agricultural population/total population
	Export/import
	Food production/food demand
Soil quality	Soil physical indicators (e.g. bulk density, clay content, water infiltration rate, tilth, penetration resistance, soil pH, water-holding capacity, waterlogging, soil loss, etc.)
	Soil chemical indicators (e.g. total organic C, total and available N, P and other nutrients, nutrient-supplying capacity, cation exchange capacity (CEC), salinity, accumulation of toxic compounds, etc.)
	Soil biological indicators (e.g. soil microbial biomass, soil respiration, soil enzymes, biomass N, quotient of soil organic C to biomass C and total N to biomass N, diversity of microbial species, etc.)
Water availability and quality	Quantity of fresh surface water available
	Groundwater level fluctuations
	Quality of surface water and groundwater (chemical and biological quality)
Environmental services	Greenery cover/vegetation index
	Carbon sequestered
	Reduced emissions of greenhouse gases
	Reduced land degradation/rehabilitation of degraded lands
Biodiversity: socio-cultural functions	Animal population, species, etc.
	Changes in landscape and scenery
	Changes in recreational benefits (agro-ecotourism, outdoor sports, etc.)
	Changes in cultural and artistic use (e.g. motivation for books, films, advertising, etc.)
	Changes in use for religious and historical use (e.g. heritage, spiritual symbol)
	Recognition for scientific or educational purposes

Source: Wani *et al.* (2006a).

The mean internal rate of return on watershed investment is comparable with any successful government programme. It is interesting to note that 35% of watersheds yielded more than a 30% internal rate of return (Fig. 14.2). About 5% of watersheds performed very poorly; the internal rate of return was less that 10%. This evidence suggests that the watershed programmes performed reasonably well in the fragile and challenging environments. The investment was logically justified, which was responsible for raising the income levels and reducing poverty of the beneficiaries in the target domains.

Benefits from watershed programmes were conspicuously more in the low-income regions as compared with the high-income regions

Table 14.2. Summary of benefits from the sample watershed studies[a].

Indicator	Particulars[b]	Unit	No. of studies	Mean	Mode	Median	Minimum	Maximum	t-value
Efficiency	B/C ratio	Ratio	128	2.14	1.70	1.81	0.82	7.06	21.25
	IRR	Per cent	40	22.04	19.00	16.90	1.68	94.00	6.54
Equity	Employment	Person-days/ha/year	39	181.50	75.00	127.00	11.00	900.00	6.74
Sustainability	Irrigated area	Per cent	97	33.56	52.00	26.00	1.37	156.03	11.77
	Rate of run-off	Per cent	36	−13.00	−33.00	−11.00	−1.30	−50.00	6.78
	Soil loss	t/ha/year	51	−0.82	−0.91	−0.88	−0.11	−0.99	39.29
	Cropping intensity	Per cent	115	63.51	80.00	41.00	10.00	200.00	12.65

[a]Source: Joshi *et al.* (2005); [b]B/C = benefit–cost, IRR = internal rate of return.

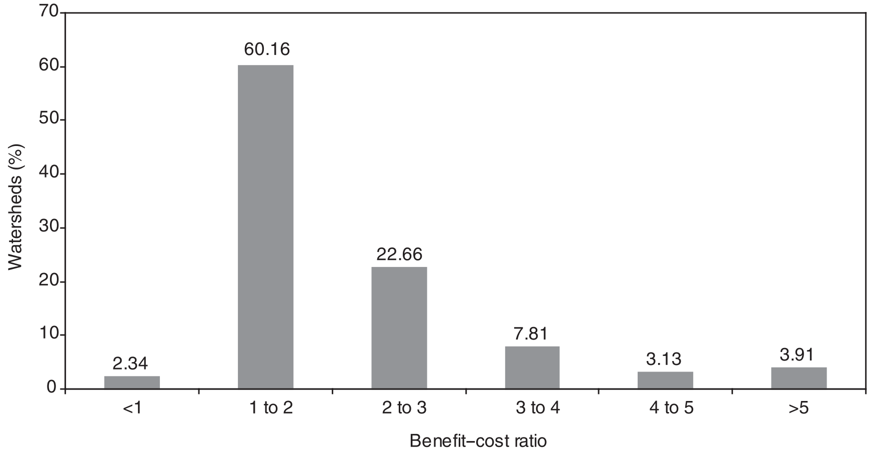


Fig. 14.1. Distribution (%) of watersheds according to benefit–cost ratio.

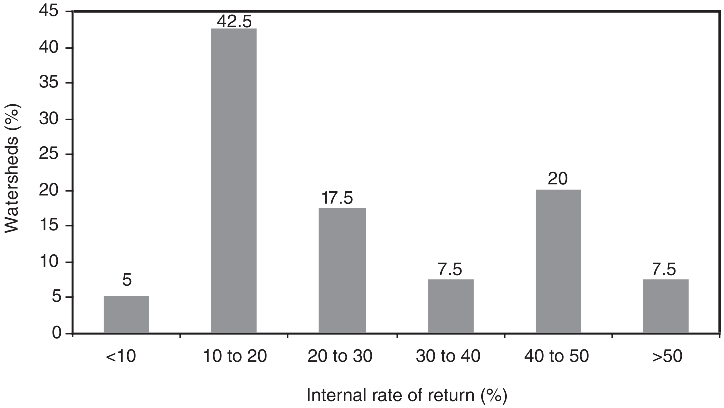


Fig. 14.2. Distribution (%) of watersheds according to internal rate of return (Source: Joshi *et al.*, 2005).

(Table 14.3). The benefit–cost ratio was 2.46 in low-income regions as compared with 1.98 in high-income regions. The corresponding figures for annual employment generation were 175 and 132 person-days/ha. The low-income regions call for such investments to enhance income levels of the rural poor. This suggests that watershed programmes should receive higher priority by the government in medium- and low-income regions. Such investments will not only raise income and employment opportunities in the backward regions but also contribute in conserving soil and water resources.

The study by Fan and Hazell (1997) demonstrates that the returns to investment in inputs as well as research were higher for dryland areas than for irrigated areas. Farmers in these regions could not invest due to low income and limited opportunities. Government intervention through watershed programmes would benefit the rural poor in the low-income regions. Ironically, the participation of beneficiaries in planning and execution of the watershed in the low-income regions was observed to be less than that in the higher-income regions.

This implies that poor rural households were less involved in planning and decision-making processes in the watersheds. However, the rural poor in the low-income regions were offering their labour in various activities launched in the watershed. In fact, for the smaller farmers and the landless labourers in the watershed, there is often little prospect for development beyond the employment generated from the watershed works over the project period (Farrington *et al.*, 1999). Perhaps greater involvement of the beneficiaries would yield higher dividends from the investment in watershed-related activities as active people's participation is a critical factor for success and sustainability of watershed programmes. The available evidence also confirms that the watershed programmes with high people's participation were able to harness more benefits. Joshi *et al.* (2005) estimated that the benefit–cost ratio was much more (2.4) in watersheds where people's participation was high in comparison with the watersheds with low participation (1.24). The other impact indicators were also far ahead in watersheds having greater people's participation.

The above evidence reveals that people's participation was the key determinant in the success of the WDPs. It implies that people's participation is not only critical during the implementation phase of watersheds but beyond the actual investment phase. In the absence of active involvement of the stakeholders, the watershed programmes would not be sustained. However, there are other enabling factors too that determine the performance of watershed programmes. A strong linkage of the

Table 14.3. Summary of benefits from the watershed studies according to economic status of the region[a].

			Per capita income of the region[b]		
Indicator	Particular	Unit	High	Medium	Low
Efficiency	B/C ratio	Ratio	1.98	(16.86)	2.21
			(12.28)	2.46	(7.73)
Equity	Employment	Person-days/ha/year	132.01	(4.14)	161.44
			(5.29)	175.00	(4.66)
Sustainability	Irrigated area	Per cent	40.34	(9.73)	23.01
			(6.24)	36.88	(4.19)
	Cropping intensity	Per cent	77.91	(8.67)	36.92
			(11.99)	86.11	(7.64)
	Rate of run-off reduced	Per cent	12.38	(5.31)	15.82
			(3.39)	15.43	(6.01)
	Soil loss reduced	t/ha/year	0.82	(40.32)	0.88
			(37.55)	0.69	(4.60)
Extent of people's participation			High	High	Low

[a] Source: Joshi *et al.* (2005); [b] Figures in parentheses are t-values. Includes the states having per capita AgGDP (1996–1997) greater than Rs 4000 for high-, between Rs 2000 and Rs 4000 for medium-, and below Rs 2000 per annum for low-income regions.

watershed programme with various institutions is critical for yielding desired outputs. Effective linkages between SHGs or users' associations and various institutions would sustain the watershed programme.

Drivers of Collective Action and Success

People's participation

Active people's participation is a prerequisite for the success of WDPs. Involvement of local stakeholders in planning, development and execution of the watershed activities is crucial. The watershed is a community development approach and hence it calls for community participation and collective action. It is necessary because individual choices have collective consequences in the watershed framework. Action of one group of farmers in one location affects (adversely or favourably) another group of farmers in a different location (off-site impact). Such externalities influence the performance of the watershed at large. Often the different groups and locations have conflicting objectives with respect to their investment priorities and enterprise choices. These need to be converted into opportunities. The actions of all the farmers in the watershed should converge in such a way that the positive externalities are maximized and negative ones are minimized. To achieve this, the community or stakeholders have to develop their own rules, which resolve their conflicting objectives. It is believed that better organized and effective people's participation would yield higher benefits.

The first-generation watershed programmes in the country were supply driven. The government officials used to identify locations and decide various activities for implementation of watershed programmes, which were funded by central and state governments. This top-down approach did not match the needs of stakeholders in the watershed. In the absence of people's participation, the potential benefits of the watershed programmes could not be realized. To overcome this problem, the concept of Participatory Integrated Development of Watershed (PIDOW) was initiated in the 1980s. However, only a partial success could be achieved, and some radical steps were taken to involve the local stakeholders/people in planning, formulation and implementation of watershed programmes in the country. In due course, the people's institutions, such as *Zila Parishad*, SHGs and watershed-implementing committees, were gradually involved in the project management system. With more funds allocated for watershed development, several NGOs aggressively participated in implementing this programme and demonstrated the importance of people's involvement in the success of the watersheds. Most of the arrangements were informal and varied across watersheds and implementing agencies. To make it formal, the 1994 watershed guidelines specifically included people's involvement as one of the conditions in the watershed development. It is important that people come forward and participate voluntarily. Only voluntary participation (not forced) would sustain the watershed programme. It is therefore important to identify conditions under which the watershed beneficiaries would involve themselves in implementation, during the project tenure and maintenance of structures after the project is formally over.

Bottom-up approach

The watershed that involves activities which are able to cater to the specific needs of local people certainly attracts higher people's participation. It is therefore essential to ensure that once the watershed is identified, the needs of the stakeholders must be assessed together by the implementing agency and the stakeholders. Since a watershed has diverse groups of beneficiaries, all genuine and valid needs of each and every group should be appropriately addressed in the watershed. There are reports which state that in many watersheds only influential and large farmers were involved and the small and marginal farmers were not involved. Besides, there was evidence that most of the watershed programmes were not sensitive to the needs of women and landless labourers. Often the women and landless labourers were silently left out of watershed-related decision-making processes (Meinzen-Dick *et al.*, 2004; Sreedevi and Wani, 2007). The integration of small and marginal farmers, women and landless labourers into the process requires conscious efforts right from the beginning.

Tangible economic benefits to individuals

In spite of a bottom-up participatory approach for planning and implementation of watershed development, community participation was not forthcoming in most of the watershed programmes. The main reason for the low or contractual mode of participation was that large numbers of small and marginal farmers were not getting tangible economic benefits as productivity-enhancement initiatives were missing to large extent. Improved groundwater availability benefited a few well-to-do farmers who could invest and extract the groundwater. Such well-to-do farmers, who were beneficiaries of the improved groundwater availability, had no time to participate. On the other hand, large numbers of small and marginal farmers who had time to participate were not getting any tangible benefits. One of the important drivers of success in a consortium approach was tangible economic benefits to large numbers of farmers through increased crop productivity on individual farms through *in-situ* rainwater conservation and its efficient use, with improved crops/cultivars, nutrient, water and pest management options (Wani *et al.*, 2002). Through this approach, a greater number of farmers started participating in WDPs as they derived tangible economic benefits from the productivity-enhancement activities from the first season itself.

Knowledge-based entry point activity

In most watershed programmes, entry point activity (EPA), as identified by the community, is undertaken under the project to build rapport with the community through activities such as construction of a meeting room, school, classroom, borewell pump, drinking water tank, etc., using project financial resources allocated for EPA. However, it was observed that such cash-based EPA passed on a wrong signal to the community that all activities can be undertaken through project funds, which the community capitalized on without contributing their share. Such a subsidy-dependency approach never got community ownership, resulting in the neglect of the resources invested. The ICRISAT-led consortium has developed knowledge-based EPA to build rapport with the community using soil analysis or introduction of disease-tolerant cultivars, etc., which provided free knowledge but farmers had to pay for the material (Wani *et al.*, 2006a).

The knowledge-based EPA ensured that demand-driven technologies were evaluated by the farmers rather than supply-driven ones provided by the project staff, which resulted in a cooperative and consultative mode of community participation, as against the contractual mode in the case of direct cash-based EPA. Knowledge-based EPA was one of the important drivers of collective action in the community watersheds developed through the consortium approach for technical backstopping (Sreedevi *et al.*, 2004; Shiferaw *et al.*, 2006).

Watershed institutions/self-help groups

The next stage of people's participation is even more critical. It denotes the phase of implementation where various interventions are being made. This stage requires regular monitoring because success of the watershed depends upon how effectively the stakeholders are monitoring the progress. Evidence shows that some successful watersheds constituted informal groups for regular monitoring of watershed activities. However, there was considerable difference between these groups. For instance, some watersheds constituted formal users' associations. The users' groups were found to be active during the implementation phase only and had no mechanisms in place to meet regularly once the construction activity was completed, unlike the SHGs, which met regularly for financial transactions. In a recent study of institutional arrangements in different watershed programmes, Sreedevi *et al.* (2007) observed that the area groups approach adopted in the Sujala watershed programme in Karnataka was far superior to the users' groups approach in terms of functional efficiency, sustainability and regularity, as the membership was voluntary for undertaking project activities in their area. In the same study, membership criteria and actor linkages in the APRLP–DFID programme, the Sujala watershed, the Indo-German Watershed Development Programme and the Hariyali guidelines-based watershed programme were studied. It was concluded that representation in the watershed committee for women SHGs in the Sujala and APRLP programmes was effective for women's participation and decision making, whereas the community was not effective/functional in the Hariyali programme watersheds. The *Gram Panchayat* had a major role in Hariyali watersheds but it was not the same in other programmes. Similarly, the apparent convergence of line departments in Hariyali watersheds was evident on paper only, and the effective and close working relationship between watershed development teams, the watershed committee and area groups was found in the Sujala programme (Sreedevi *et al.*, 2007). Concepts such as *Mitra Kisan* or *Gopal Mitra* have shown mixed results across different watersheds in different states (Deshpande and Thimmaiah, 1999).

The success of watershed programmes not only relies on the watershed institutions but also depends more on how effective the credit delivery system, the input delivery system, the output markets and the technology transfer mechanisms are. It is therefore imperative to ensure that watershed programmes/institutions should also have a strong linkage with various institutions such as markets, banks, etc.

Decentralize decision-making process

Decision making is the key component of watershed programmes. The success or failure of watershed programmes very much depends on who makes decisions and how they are made. Hence, decentralization of the decision-making process is of utmost importance. Several watershed evaluation reports show that watersheds performed reasonably well where the decision-making process was decentralized. Decentralization of the decision-making processes, however, requires flexibility. Often it is noted that the rigid norms did not allow decentralization of decision making. To some extent, involvement of elected representatives of the people (Members of Legislative Assembly and Parliament) in the development process may ease the process (Joshi *et al.*, 2004). There are reports that in Madhya Pradesh a conscious effort was made since 1995 to involve elected representatives of the people. Greater involvement of local Members of Legislative Assembly and Parliament and Panchayat Raj Institutions may assume a significant role in project planning and execution, since they are the elected representatives who would like to make political mileage as a result of developmental programmes such as watersheds. In this process, they become accountable to the watershed and can be voted out in the event of tardy progress.

Commensurate benefits and costs

The watershed is a community-based approach but individual actions are also important. As stated earlier, the individual actions have collective consequences. There are many conflicting objectives among the stakeholders. Benefit-sharing is perhaps the most complex challenge in management of the watershed. In a watershed framework, often benefits are not commensurate with the cost incurred and the labour involved in the watershed activities. Sharing of benefits in accordance with the cost and contributions of the participants will go a long way in sustaining the watershed programme. For example, in the watershed framework, the farmers located at the upper reaches have to invest more but the gains of their actions are more to farmers at the middle or lower reaches (Joshi *et al.*, 1996).

Capacity building

Management of the watershed is a complex process. Many of the watershed-related activities that aim to conserve, restore and augment soil and water resources require specialized skills. The most important and also the weak link in watershed programmes is training and capacity building of all the stakeholders from farmers to policy makers (Wani *et al.*, 2008b). Most stakeholders conceive WDPs as construction of rainwater-harvesting structures and never go beyond to include productivity enhancement, income-generating activities, livestock-based activities, institutions, monitoring and evaluation mechanisms, wasteland development, market linkages, etc. Most stakeholders emphasize the area of their expertise; for example, NGOs emphasize social mobilization and rainwater harvesting, and watershed development teams and technocrats emphasize technologies and overlook holistic integration. Technical backstopping through the consortium approach provides opportunities for training and capacity development of all the actors involved. Thus, training of beneficiaries is another key element for the success of the watershed activities. Unawareness and ignorance of the stakeholders about the objectives, approach and activities is one of the reasons that affects the performance of watersheds. For example, in most watersheds not only the farmers but also most stakeholders are not aware of the major constraints for increasing productivity or actual potential of the watershed (Wani *et al.*, 2003b,c). The stakeholders must be aware about the importance of various activities in the watersheds, and their benefits in terms of economic, social and environmental aspects. Many actions by the stakeholders in the watershed are being taken in ignorance, which adversely affects the income and environment of other stakeholders and locations. Educating all the stakeholders would minimize such actions and conflicts and maximize benefits from the watershed. The Professor Hanumantha Rao Committee and Sri Eshwaran Committee have strongly recommended the need for training of all stakeholders in the watershed. These recommendations must be adhered to make the programme more participatory and successful.

Targeted activities for women and vulnerable groups

In order to enlist active participation of women and vulnerable groups, Sreedevi and Wani (2007) suggested targeted activities that benefit these groups economically. More income-generating, commercial-scale activities for women resulted in better participation as well as improved decision-making power and social status for women in the family and society. The mere presence of women members on the watershed committee had no real impact on women as they were not effective in the decision-making process in the committee (Seeley *et al.*, 2000). Harnessing gender power by balancing activities for men and women, farmers and landless people was found to be effective in enhancing the impact of community watershed programmes (Sreedevi and Wani, 2007).

Agroecoregion-specific technologies

Agroecological differences play a deterministic role in the success of watershed programmes. For example, meta-analysis of watershed case studies revealed that the current technologies and interventions showed better impact in terms of benefit–cost ratio and internal rate of return in the regions receiving average annual rainfall between 700 and 1100 mm rainfall, whereas the regions with rainfall less than 700 mm and higher than 1100 mm failed to generate equal benefits because of scarcity of water on one hand and excessive water availability on the other (Joshi *et al.*, 2005). This calls for an endeavour to identify and adopt specific watershed development technologies for <700 and >1100 mm rainfall zones (Wani *et al.*, 2007). The current practice of allocating a greater proportion of resources for rainwater-harvesting structures, too large a proportion, needs close scrutiny. Wani *et al.* (2003a) have demonstrated the benefits of low-cost water-harvesting structures throughout the toposequence, which benefited a greater number of farmers than construction of masonry check-dams.

Size of the watershed

The size of the watershed has a high significance in the success of watershed programmes. Based on the economic efficiency parameters, Joshi *et al.* (2005) estimated that the performance of microwatersheds with an area up to 1250 ha was 42% less than that of large size (>1250 ha) watersheds. Thus, there is a need to reconsider the standard 500-ha watersheds and address the issues of suitable watershed size and social problems associated with administrative institutions (villages). A cluster of watersheds needs to be developed simultaneously instead of developing microwatersheds in a scattered manner (Wani *et al.*, 2006a).

Upscaling the benefits of watershed development programmes

For upscaling the benefits of integrated watershed management, there is a need to have an articulated strategy based on the main pillar of capacity building of all the stakeholders from farmers–researchers–development workers, policy makers and development investors.

New scientific tools, such as remote sensing (RS), geographical information systems (GIS), digital terrain modelling for estimating run-off and soil loss, and crop simulation modelling for the analysis of long-term potential productivity, need to be used as the planning tools. These tools provide the capabilities for extrapolating and implementing the technologies to other larger watersheds. To scale up the benefits from the innovative farmer participatory consortium model for managing watersheds in Kothapally, Rangareddy district, the following process was adopted (Wani *et al.*, 2003c) (Fig. 14.3).

In the process of scaling-up, it is envisaged that three to four nucleus watersheds are selected in each district, by adopting the principles of 'seeing is believing' participatory research and development (PR&D). In the first year, nucleus watersheds are established and the implementing NGO and farmers undertake the PR&D approach to select suitable interventions. The process of selecting nucleus watersheds is a guided process. An additional requirement is that the project-implementing NGOs should have the capacity and a good track record of implementing watershed projects in the district. The nucleus watershed-implementing NGO becomes the pilot trainer for other NGOs in the district. In addition, the pilot NGO transfers the knowledge gained from the nucleus watershed to other watershed projects implemented by their staff in the area, and so knowledge dissemination takes place. Each nucleus watershed has four satellite watersheds, and the farmers and SHG members from the nucleus watershed become the master trainers in the district for the satellite watersheds.

Emphasis in this strategy is on capacity building and empowerment of the NGOs, extension workers, farmers and SHG members. In order to further extend knowledge on the management of natural resources through integrated genetic and natural resources management (IGNRM), information and communication technology is used.

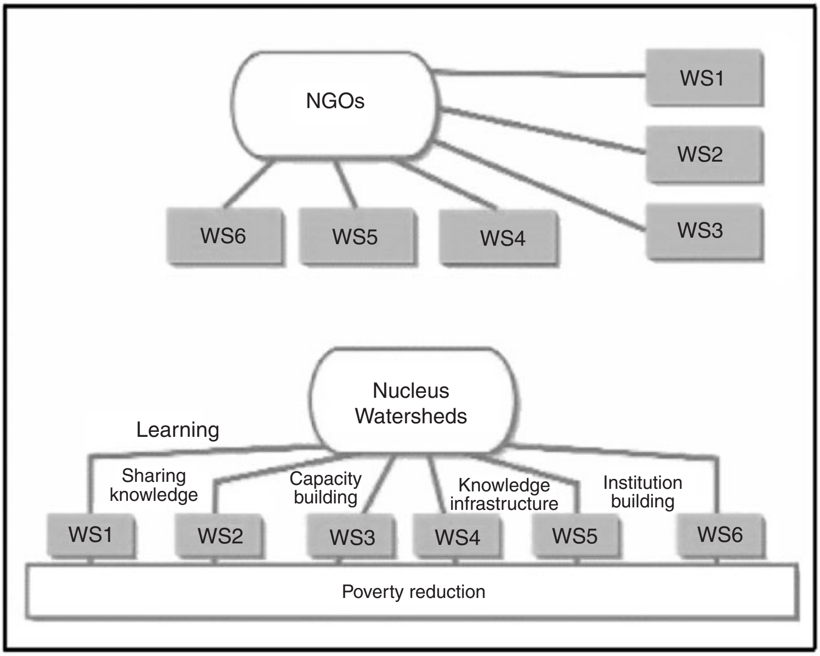


Fig. 14.3. Scaling-out the benefits of watershed (WS) development.

Adarsha watershed, Kothapally, has served as a benchmark or nucleus watershed and has demonstrated the benefits of integrated watershed management. The technology has been adopted in watersheds of neighbouring villages and other areas by farmers with little technical support from the consortium. The satellite watersheds, which are similar in terms of soils, climate and socio-economic patterns, can achieve broad impacts by adopting these technologies. The ICRISAT consortium focused on training farmers, personnel from development agencies and NGOs through demonstrations of different technologies on benchmark watersheds, and also acts as a mentor for technology backstopping. The farmers' community, through village institutions, took responsibility for all activities of implementation and monitoring. Government and non-governmental agencies catalysed the process. The important aspect while evaluating and scaling-out this approach is that the concerned line departments of the government need to be included in the consortium from the beginning, along with other partners. The role of policy makers and development investors is very critical, and sensitization of these stakeholders played a major role in scaling-out the benefits in Asia.

In the DFID-supported project of Andhra Pradesh Rural Livelihoods Programme (APRLP), the scaling-up approach has been extended to 50 watersheds (10 nucleus and 40 satellite) in three districts of Andhra Pradesh, and with support from the Sir Dorabji Tata Trust it has been extended to two districts of Madhya Pradesh and one district in Rajasthan. This approach was evaluated with support from the Asian Development Bank in China, Thailand and Vietnam. Further, the World Bank-assisted Sujala Watershed Programme in Karnataka and also the Bureau of Agricultural Research, the Philippines are adopting a similar approach for scaling-out the benefits of productivity enhancement in watersheds (Wani *et al.*, 2006b). The drivers for better collective action and success of the watershed programmes are summarized in Box 14.1.

Summary and Conclusions

This chapter has documented and analysed the benefits from various watershed programmes by eliciting information from micro-level studies to give a macro dimension. It attempts to analyse the role of watersheds in augmentation of water resources in the rainfed areas of the country. However, it is clear that a programme will never succeed unless it is economically viable, and therefore economic efficiencies of the watershed programmes were also documented and analysed. It is observed that the watershed programmes have been very much effective in augmenting water resources along with conservation of soil and water in the rainfed areas. In addition, watershed programmes have also generated considerable income and employment in the fragile rainfed areas. The analysis clearly reveals that watershed development provides a sustainable option for augmentation and conservation of water resources in rainfed regions.

However, the performance of a watershed depends on certain specific prerequisites, e.g. high people's participation in watershed activities. The benefits of watershed programmes were greater where people's participation was higher. It was noted that people's participation is not only important during the phase of implementa-

Box 14.1. Drivers of better collective action and success of watershed programmes:

- Good local leadership.
- Predisposition to collective work.
- The Novel Approach to watershed management with technical backstopping and convergence.
- Equal partnership, trust and shared vision among the consortium partners.
- Transparency and social vigilance in the financial dealings.
- High confidence of the farmers.
- Low-cost structures and equitable sharing of benefits.
- Knowledge-based entry point activities.
- Capacity building and skill development.

tion of watershed development activities but beyond the actual investment phase. A few conditions are critical to ensure people's participation. Involvement of all stakeholders (including women and landless labourers) in programme implementation and monitoring is imperative for the success of the watershed programmes. Decentralization of the decision-making process and involvement of elected representatives and Panchayat Raj Institutions in decision making enhance the chance of success. Sharing of benefits from the watershed programme is extremely critical. It is essential that benefits of all stakeholders should match their contributions and costs. Besides all these, functional and effective linkages among watershed institutions and other institutions, such as markets, banks, etc., are imperative for success. Watersheds, with sagacious institutional arrangements and voluntary participation of all stakeholders, would definitely be a boon for augmentation of water resources in the fragile and rainfed areas and set the path of a second green revolution in the country.

References

Deshpande, R.S. and Thimmaiah, G. (1999) Watershed development approach and experience of national watershed development program in the country. *Journal of Rural Development* 18(3), 453–469.

DOLR (Department of Land Resources) (2003) *Guidelines for Hariyali* (http://dolr.nic.in/HariyaliGuidelines.htm). DOLR, Ministry of Rural Development, Government of India, New Delhi, India.

Fan, S. and Hazell, P. (1997) Should India invest more in less-favoured areas? Environment and Production Technology Division Discussion Paper No. 25. International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Farrington, J. and Lobo, C. (1997) Scaling up participatory watershed development in India: lessons from the Indo-German Watershed Development Program. Natural Resource Perspective, No. 17, February 1997. ODI (Overseas Development Institute), London, UK.

Farrington, J., Turton, C. and James, A.J. (eds) (1999) *Participatory Watershed Development: Challenges for the 21st Century*. Oxford University Press, New Delhi, India.

Government of India (1994) *Guidelines for Watershed Development*. Department of Land Resources, Ministry of Rural Development, Government of India, New Delhi, India.

Government of India (2005) Serving Farmers and Saving Farming – 2006: Year of Agricultural Renewal. Third Report. December 2005. National Commission on Farmers, Ministry of Agriculture, Government of India, New Delhi, India.

Gupta, S.K. and Deshpande, R.D. (2004) Water for India in 2050: first-order assessment of available options. *Current Science* 86 (9), 1216–1224.

Hanumantha Rao, C.H. (2000) Watershed development in India: recent experience and emerging issues. *Economic and Political Weekly* 35(45), 3943–3947.

Joshi, P.K., Wani, S.P., Chopde, V.K. and Foster, J. (1996) Farmers' perception of land degradation – a case study. *Economic and Political Weekly* 31(26), A 89–92.

Joshi, P.K., Laxmi, T., Jha, A.K. and Shiyani, R.L. (2003) Impact of watershed programs and people's participation. In: Pal, S., Mruthyunjaya, Joshi, P.K. and Saxena, R. (eds) *Institutional Change in Indian Agriculture*. National Centre for Agricultural Economics and Policy Research, New Delhi, India, pp. 81–96.

Joshi, P.K., Pangare, V., Shiferaw, B., Wani, S.P., Bouma, J. and Scott, C. (2004) Socioeconomic and policy research on watershed management in India: synthesis of past experiences and needs for future research. *Global Theme on Agroecosystems Report No. 7.* International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Joshi, P.K., Jha, A.K., Wani, S.P., Joshi, L. and Shiyani, R.L. (2005) Meta-analysis to assess impact of watershed programme and people's participation. Research Report No. 8. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India and Asian Development Bank, Manila, the Philippines.

Kerr, J., Pangare, G., Pangare, L.V. and George, P.J. (2000) An evaluation of dryland watershed development projects in India. EPTD Discussion Paper 68. Environment and Policy Production Technology Division, International Food Policy Research Institute (IFPRI), Washington, DC, USA.

Meinzen-Dick, R., DiGregorio, M. and McCarthy, N. (2004) Methods for studying collective action in rural development. *Agricultural Systems* 82, 197–214.

Molden, D., Frenken, K., Barker, R., de Fraiture, C., Mati, B., Svendsen, M., Sadoff, C. and Finlayson, C.M. (2007) Trends in water and agricultural development. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK, and International Water Management Institute, Colombo, Sri Lanka, pp. 57–89.

Pathak, P., Sahrawat, K.L., Rego, T.J. and Wani, S.P. (2004) Measurable biophysical indicators for impact assessment: changes in soil quality. In: Shiferaw, B., Freeman, H.A. and Swinton, S.M. (eds) *Natural Resources Management in Agriculture: Methods for Assessing Economic and Environmental Impacts*. CAB International, Wallingford, UK, pp. 55–74.

Pingali, P. and Raney, T. (2005) From the green revolution to the gene revolution: how will the poor fare? ESA Working Paper No: 05–09. Food and Agriculture Organization of the United Nations, Rome, Italy.

Rockström, J., Hatibu, N., Oweis, T. and Wani, S.P. (2007) Managing water in rainfed agriculture. In: Molden, D. (ed.) *Water for Food, Water for Life: a Comprehensive Assessment of Water Management in Agriculture*. Earthscan, London, UK and International Water Management Institute (IWMI), Colombo, Sri Lanka, pp. 315–348.

Samra, J.S. (1998) Watershed management for sustainable agriculture. In: Dhaliwal, G.S., Arora, R., Randhawa, N.S. and Dhawan, A.K. (eds) *Ecological Agriculture and Sustainable Development,* Vol. 1. Centre for Research in Rural and Industrial Development, Chandigarh, India, pp. 147–155.

Seeley, J., Menaakshi, B. and Madhu, S. (2000) Women's participation in watershed development in India. Gatekeeper Series No. 92. International Institute for Environment and Development, London, UK.

Shah, A. (2007) Benchmark survey for impact assessment of participatory watershed development projects in India. Draft report submitted to Planning Commission, Government of India, New Delhi, India.

Sharma, R. (2002) Watershed development adaptation strategy for climate change. Presented in South Asia Expert Workshop on Adaptation to Climate Change for Agricultural Productivity. Organized by the Government of India, UNEP and CGIAR in New Delhi, India.

Shiferaw, B., Bantilan, C. and Wani, S.P. (2006) Policy and institutional issues and impacts of integrated watershed management: experiences and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C. (eds) *Integrated Management of Watersheds for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-Arid South Asia*. Proceedings of the International Workshop held at ICRISAT, Nairobi, Kenya, 6–7 December 2004. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 37–52.

Sreedevi, T.K. and Wani, S.P. (2007) Leveraging institutions for enhanced collective action in community watersheds through harnessing gender power for sustainable development. In: Mudrakartha, S. (ed.) *Empowering the Poor in the Era of Knowledge Economy*. VIKSAT, Ahmedabad, Gujarat, India, pp. 27–39.

Sreedevi, T.K., Shiferaw, B. and Wani, S.P. (2004) *Adarsha Watershed, Kothapally: Understanding the Drivers of Higher Impact*. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Sreedevi, T.K., Wani, S.P., Sudi, R., Patel, M.S., Jayesh, T., Singh, S.N. and Shah, T. (2006) On-site and off-site impact of watershed development: a case study of Rajasamadhiyala, Gujarat, India. *Global Theme on Agroecosystems Report No. 20*. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Sreedevi, T.K., Vamsidhar Reddy, T.S. and Wani, S.P. (2007) Institutional Mechanisms in Selected Watershed Programs in India. Paper presented during Review Meeting of 'A Comprehensive Assessment of Watershed Programs in India' at ICRISAT, Patancheru, India on 23 July 2007.

Wani, S.P. and Ramakrishna, Y.S. (2005) Sustainable management of rainwater through integrated watershed approach for improved rural livelihoods. In: Sharma, B.R., Samra, J.S., Scott, C.A. and Wani, S.P. (eds) *Watershed Management Challenges: Improved Productivity, Resources and Livelihoods*. International Water Management Institute (IWMI), Sri Lanka, pp. 39–60.

Wani, S.P., Pathak, P., Tam, H.M., Ramakrishna, A., Singh, P. and Sreedevi, T.K. (2002) Integrated watershed management for minimizing land degradation and sustaining productivity in Asia. In: Adeel, Z. (ed.) *Integrated Land Management in the Dry Areas*. Proceedings of Joint UNU–CAS International Workshop, Beijing, China, United Nations University, Tokyo, Japan, pp. 207–230.

Wani, S.P., Pathak, P., Jangawad, L.S., Eswaran, H. and Singh, P. (2003a) Improved management of vertisols in the semi-arid tropics for increased productivity and soil carbon sequestration. *Soil Use and Management* 19, 217–222.

Wani, S.P., Pathak, P., Sreedevi, T.K., Singh, H.P. and Singh, P. (2003b) Efficient management of rainwater for increased crop productivity and groundwater recharge in Asia. In: Kijne, J.W., Barker, R. and Molden, D. (eds) *Water Productivity in Agriculture: Limits and Opportunities for Improvement*. CAB International, Wallingford, UK, pp. 199–215.

Wani, S.P., Singh, H.P., Sreedevi, T.K., Pathak, P., Rego, T.J., Shiferaw, B. and Iyer, S.R. (2003c) Farmer participatory integrated watershed management: Adarsha watershed, Kothapally, India. An innovative and upscalable approach. Case 7. In: Harwood, R.R. and Kassam, A.H. (eds) *Research Towards Integrated Natural Resources Management: Examples of Research Problems, Approaches and Partnerships in Action in the CGIAR*. Interim Science Council, Consultative Group on International Agricultural Research, Washington, DC, USA, pp. 123–147.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., Long, T.D., Wangkahart, T., Shiferaw, B., Pathak, P. and Kesava Rao, A.V.R. (2006a) Issues, concepts, approaches and practices in the integrated watershed management: experience and lessons from Asia. In: Shiferaw, B. and Rao, K.P.C (eds) *Integrated Management of Watershed for Agricultural Diversification and Sustainable Livelihoods in Eastern and Central Africa: Lessons and Experiences from Semi-Arid South Asia*. Proceedings of the International Workshop held at ICRISAT, Nairobi, Kenya, 6–7 December 2004. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India, pp. 17–36.

Wani, S.P., Ramakrishna, Y.S., Sreedevi, T.K., Wangkahart, T., Thang, N.V. Somnath Roy, Zhong Li, Yin Dixin, Zhu Hong Ye, Chourasia, A.K., Shiferaw, B., Pathak, P., Piara Singh, Ranga Rao, G.V., Mula, R.P., Smitha Sitaraman and Communication Office at ICRISAT (2006b) *Greening Drylands and Improving Livelihoods*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India.

Wani, S.P., Sreedevi, T.K., Rockström, J., Wangkahart, T., Ramakrishna, Y.S., Yin Dxin, Kesava Rao, A.V.R. and Zhong Li (2007) Improved livelihoods and food security through unlocking the potential of rainfed agriculture. In: Aswathanarayana, U. (ed.) *Food and Water Security*. Indian Science Congress, Visakhapatnam, India, pp. 89–106.

Wani, S.P., Joshi, P.K., Raju, K.V., Sreedevi, T.K., Wilson, M., Shah, A., Diwakar, P.G., Palanisami, K., Marimuthu, S., Ramakrishna, Y.S., Meenakshi Sundaram, S.S. and D'Souza, M. (2008a) *Community Watershed as Growth Engine for Development of Dryland Areas – Executive Summary. A Comprehensive Assessment of Watershed Programs in India*. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Wani, S.P., Sreedevi, T.K. and Marimuthu, S. (2008b) *A Comprehensive Assessment of Watershed Programs in India*. Proceedings of the Review Meeting and Component Workshops, 23–27 July 2007, ICRISAT. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

Index

Page numbers in **bold** refer to figures and tables