Climate Change: Greenhouse Gas Emission in Rice Farming and Mitigation Options

Edited by

P. Bhattacharyya, A.K. Nayak,
R. Raja and K.S. Rao

CENTRAL RICE RESEARCH INSTITUTE, CUTTACK

Climate Change: Greenhouse Gas Emission in Rice Farming and Mitigation Options

Edited by

P. Bhattacharyya
A.K. Nayak
R. Raja
K.S. Rao

CENTRAL RICE RESEARCH INSTITUTE
(Indian Council of Agricultural Research)
Cuttack 753 006, Odisha, India

Citation:

Bhattacharyya, P., Nayak, A.K., Raja, R. and Rao, K.S. (Eds.) 2012. Climate change: Greenhouse gas emission in rice farming and mitigation options. Central Rice Research Institute, Cuttack, Odisha, India. p.165.

ISBN 81-88409-12-X

Published by:

Director
Central Rice Research Institute
Cuttack 753 006, Odisha, India
Phone: 91-671-2367757 (Office)
91-671-2367768-783 (EPABX)
Fax: 91-671-2367663
Email: directorcrri@sify.com | crrictc@nic.in

Design and layout:

Sunil Kumar Sinha

The views expressed in this book are of authors and do not necessarily reflect those of CRRI, Cuttack.

Printed at : Print-Tech Offset Pvt. Ltd., Bhubaneswar 751 024, Odisha, India

डा. त्रिलोचन महापात्र
निदेशक
Dr. Trilochan Mohapatra, FNASc, FNAAS
Director

केन्द्रीय चावल अनुसंधान संस्थान
भारतीय कृषि अनुसंधान परिषद
कटक (ओड़ीशा) ७५३००६, भारत

Central Rice Research Institute
Indian Council of Agricultural Research
Cuttack (Odisha) 753 006, India

FOREWORD

In the context of the changed climatic scenario and its effect on crop productivity, the soil nutrient status has assumed greater significance and is of worldwide concern for the environmental sustainability. Rice is the major cereal crop feeding two-thirds of the global population. Rice also serves as a major sink of organic carbon in the soil, while, on the contrary, its cultivation contributes to the emission of greenhouse gases (GHGs) to the atmosphere. Modern research demands adoption strategies for sustaining higher yield, while retaining the nutrients in soil under changed climate.

India has one of the most variable climates in the world, and a history of facing the extremes that destabilize production and threatens sustained agricultural growth. It is not surprising that our society is increasingly seeking information about the causes of the changing climate, and how we might adapt and respond to it. This book seeks to provide a broad coverage of topics with in-depth analysis that this complex issue demands and deserves. The chapters cover most aspects that are related to the global and Indian climates including how greenhouse gases affect climate; its modeling and the strategies to adapt and mitigate to reduce greenhouse gas emissions. These aspects are all important as we seek a comprehensive response as researchers, policy makers and public at large to climate change.

For improved soil health and sustainable agriculture, various integrated nutrient management options developed region-wise should be promoted more vigorously for enhancing soil productivity, food security, improved livelihoods and most importantly framing strategies to cope up with climate change. The editors have synthesized the contributions from scientists of ICAR research institutions and Agricultural universities. The present compilation is a state-of-the-art report on the issues concerning climate change, soil carbon dynamics and greenhouse gas emission in relation to rice ecosystem. I congratulate the editors and authors for their painstaking efforts in bringing out this useful compendium that would serve as reference material.

(T. Mohapatra)

Cuttack
March, 2012

PREFACE

The general public and the scientific community are increasingly focusing on the impact of global climate change on the terrestrial ecosystem, with particular attention being paid to carbon dioxide (CO_2), CH_4 and N_2O as major greenhouse gases (GHGs). Mitigation of these GHGs is an important goal for humanity. Soil organic carbon (SOC) pool is the largest among the terrestrial carbon pools. The restoration of SOC pool in arable lands represents a potential sink for atmospheric CO_2. The management and enhancement of SOC with the reduction in GHG emission is important for sustainable agriculture. Carbon sequestration in soil has been identified as one of the options for moderating atmospheric CO_2 concentration. Terrestrial ecosystems particularly agricultural ecosystems are the focus of intensive research on the soil carbon and nitrogen dynamics because of their importance in the global carbon and nitrogen cycle and GHG emission.

There are growing global concerns about the response of cereal crops especially rice to the climate change scenario. Rice is the staple food of more than 50% of the world population. It accounts for 30 to 76% of the total calorie intake by more than 3 billion Asians. More than 90% of rice is produced and consumed in Asian countries. Hence the acclamatory responses of rice to the rapidly changing environment and understanding the potential impacts of multiple interacting factors (water availability, temperature, soil nutrition and CO_2) have become a subject of debate over the past two decades. The National Agricultural Innovation Project (NAIP) of ICAR initiated research on soil organic carbon dynamics under changing climatic scenario in a consortium mode. The present compendium is a compilation of research findings on soil organic carbon and nitrogen dynamics in rice, GHG emission and various mitigation options for rice farming and adoption strategies, management options for enhancing carbon sequestration and reducing nitrogen loss from the rice systems. Other climate change related issues in rice farming such as excess water situation, changing microbial diversity and grain quality were covered lucidly. The financial support of NAIP (Component 4-2031) for bringing out this publication is highly acknowledged. We hope this book will be a useful resource material for students, academician, researchers, planners and policy makers to understand the various facets of the climate change research in relation to rice farming.

Editors

CONTENTS

Contd.....

Chapter 1

Greenhouse gas emission from rice: Issues, monitoring and budgeting

P. Bhattacharyya[1*], S. Neogi[1], K.S. Roy[1], K.S. Rao[1], A.K. Nayak[1] and R.K. Bajpai[2]
[1]Central Rice Research Institute, Cuttack, Odisha, India
Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chattisgarh, India
[*]e-mial: pratap162001@yahoo.co.in

There has been a drastic increase in the atmospheric concentration of carbon dioxide (CO_2) methane (CH_4), nitrous oxide (N_2O) and other green house gases (GHGs) since the industrial revolution. The atmospheric concentration of CO_2 has increased from 280 parts per million by volume (ppmv) in 1750 to 379 ppmv in 2005 and is currently increasing at the rate of 1.9 ppmv yr^{-1} (IPCC, 2007). Atmospheric CH_4 concentration has increased from about 715 to 1774 parts per billion by volume (ppbv) in 2005 over the same period and is increasing at the rate of 7 ppbv yr^{-1} (IPCC, 2007). Similarly, the atmospheric concentration of N_2O has increased from about 270 ppbv in 1750 to 319 ppbv in 2005 and is increasing at the rate of 0.8 ppbv yr^{-1} (IPCC, 2007). The current radiative forcing of these trace gases (GHGs) is 1.46 W m^{-2} for CO_2, 0.5 W m^{-2} for CH_4 and 0.15 W m^{-2} for N_2O (IPCC, 2001). This anthropogenic enrichment of GHGs in the atmosphere and the cumulative radiative forcing of all GHGs have led to an increase in the average global surface temperature of 0.74°C since the late 19th century, with the current warming rate of 0.13°C $decade^{-1}$ (IPCC, 2007). The observed rate of increase of the global mean temperature is in excess of the critical rate of 0.1°C $decade^{-1}$ beyond which the ecosystems cannot adjust. These changes may affect the soil organic carbon (SOC) pools, dynamics, and structural stability and may disrupt cycles of water, carbon (C) and nitrogen (N) resulting into adverse impacts on biomass productivity, biodiversity and the environment.

The natural as well as anthropogenic activities have serious effects on the ever increasing concentrations of CO_2, CH_4, N_2O and other GHGs in the atmosphere. The heat-trapping properties of these aforesaid GHGs are well established. Greenhouse gases differ in their warming influence (radiative forcing) on the global climate system due to their different radiative properties and lifetimes in the atmosphere. Changes in the atmospheric concentrations of GHGs alter the energy balance of the climate system which leads to subsequent climate change. They affect the absorption, scattering and emission of radiation within the atmosphere and at the earth's surface. The resulting positive or negative changes in energy balance due to these factors, known as radiative forcing, is used for comparison of warming or cooling influences on global climate. Atmospheric concentrations of GHGs increase when emissions are larger than removal processes. These GHGs have profound impact on global climatic changes resulting into increase in ambient temperature which is likely to affect agriculture (IPCC, 2007). Although uncertainty exists as to how the earth's climate responds to these GHGs, there has been a significant rise in global temperatures. It is anticipated that increasing concentrations of GHGs are likely to accelerate further the rate of climate change. Scientists are expecting that the average global surface temperature could rise by 1.4°C-5.8°C by 2100 AD with significant regional variations (IPCC, 2007).

Agriculture can play an important role in mitigating three GHGs: CO_2, CH_4, and N_2O, having global warming potentials (GWP) 1, 24.5 and 320, respectively for a 100 year time horizon (IPCC, 2007). Plants absorb CO_2 from the atmosphere and extract some carbon for use in developing plant tissues. Oxygen (O_2) and CO_2 are released back into the atmosphere. When the plant dies, the carbon in the plant tissues is converted back to CO_2 if decomposition is aerobic, to CH_4 if decomposition is anaerobic, or remains in the soil as soil organic matter (SOM). Aerobic decomposition takes place where decaying plant material is either on the surface or close to it and exposed to alternating wet and dry periods. Anaerobic decomposition releases CH_4 and takes place in fields that are flooded for extended periods, such as those used for paddy rice. Rice farming plays a significant source of GHGs. Anaerobic decomposition in rice fields results in the release of substantial amounts of CH_4 into the atmosphere. The interactive nature of carbon and nitrogen cycles in rice fields demands a consideration of the other GHGs, namely, N_2O and CO_2, in view of full GWP accounting. Rice is the major cereal crop feeding two-thirds of the global population. Rice, the most important cereal after wheat, can be grown to extreme limits of temperature, day length, salinity and water supply. But, rice cultivation contributes to the emission of GHGs of concern (e.g., CH_4 and N_2O) to the atmosphere which affect adversely the atmospheric chemistry and the environment. Projected changes in global climate are expected to affect many marginal and fragile ecosystems. Rice crop is also likely to be affected by the impending changes in the environment

Rice occupies one-third of the world's crop land planted to cereals and provides 30-60% of the calories consumed by nearly three billion people (Guerra et al., 1998). Rice production is an important part of Asia's economy. But competitive market, day by day hike in input cost, ever increasing demand from all quarters and intensive agriculture are posing concern to its productivity and sustainability. A comprehensive understanding of how the physical environment affects rice yield is the key to improve agronomic production and its sustenance. In Asia, rice is the major food crop, and about 80% of it is grown under flooded conditions (Zou et al., 2005). Rice is grown in different environments ranging from tropical to temperate regions with varying climatic, edaphic, and biological conditions which naturally affect the rates of CO_2, CH_4 and N_2O emissions. These trace gas flux exchanges between paddy fields and the atmosphere is also greatly influenced by cultivation practices and field management, such as ploughing, stable manure amendment, seeding or transplanting of rice, water management, harvest, treatment of harvest residuals.

Carbon dioxide exchange between terrestrial ecosystems and the atmosphere is one of the key processes that affect atmospheric CO_2 concentration. In order to assess the role of terrestrial ecosystem in the global CO_2 budget at present, and to predict its changes in the future under global warming, long-term observation of CO_2 exchange has been done in various ecosystems in the world. Carbon di-oxide is an extremely important greenhouse gas as it contributes to increasing radiative forcing and thus to climate change as well as other negative impacts. These relationships are highly complex due to many feedbacks and interactions (Haszpra et al., 2008). Global atmospheric concentration of this gas increased about 35% from the pre-industrial time upto 2005. Worldwide variation in CO_2 concentrations is determined by the balance between sources and sinks (Vinogradova et al., 2007). Photosynthesis and natural respiration processes are linked to the superimposed effects of other factors such as fossil fuel combustion for energy purposes (specifically energy and transport sectors) and land use changes (Artus et al., 2009). Carbon di-oxide concentrations are also influenced by atmospheric processes in the boundary layer which affect their transport and dispersion (Ramonet et al., 2010). Variations in sources, biological processes, meteorological features of the boundary layer and geographical features of the area of interest are the main controlling factors for variability in CO_2 levels. By 2020, the ambient CO_2 concentration will reach 400 ppmv and by 2050, tropospheric CO_2 concentration is predicted to increase by 50%. But, on the other hand, CO_2 has a significant impact on crop photosynthesis, agricultural production and productivity.Rice soils that are flooded for long periods in the year tend to accumulate soil organic carbon (SOC),even with complete removal of the aboveground plant biomass (Bronson et al., 1997). Significant inputs of C and N are derived from the biological activity in the soil-floodwater system, and conditions are generally more favorable for the formation of conserved SOC (Olk et al 1998, Kirk and Olk 2000). In China, it is estimated that the current C sequestration rate in irrigated rice cultivation is 12 Tg C year^{-1} and that these systems have induced a total enrichment of SOC storage of about 0.3 Tg C (Pan et al., 2003)

Methane has strong infra-red and heat absorption band characteristics and worldwide its increasing concentration in the atmosphere is believed to contribute towards change in atmospheric chemistry as well as global warming (IPCC, 2007). Methane is presently the second most important GHG accounting for 15-20% of the anthropogenic radiative forcing. The major sources of CH_4 production are the rice paddies, ruminants, landfills, natural wet lands and sediments (Zhu et al., 2007). Tropospheric CH_4 has increased as a result of human activities related to agriculture, natural gas distribution and landfills. Although the tropospheric CH_4 is increasing continuously, increase of CH_4 emission has started to decline during the past two decades (IPCC, 2007). Among the sources of CH_4 irrigated rice fields are estimated to contribute between 6-8% (Tseng et al., 2010) of the total 410-660 million tons year^{-1} emitted globally (Tseng et al., 2010). Flooding of irrigated rice fields produces anaerobic soil conditions which are conducive to the production of CH_4 (Neue, 1993).

Nitrous-oxide is generated by the microbial transformation of N in soils and manures, and is often enhanced where available N exceeds plant requirements, especially under wet conditions (Oenema et al., 2005). The rice paddies act as sources of major N_2O emission upon nitrogenous fertilizer (e.g., urea) application. Nitrogenous fertilizer appears to be the single most important factor controlling N_2O emission from flooded rice fields. Actually N_2O is produced in considerable amounts both in upland (aerobic) and wetland (predominantly anaerobic) soils especially under N-fertilizer dependent agriculture. Wide variation in N_2O production exists in different rice soils.

Therefore, it is now evident that the flooded rice paddies are one of the most important sources of CH_4 and N_2O emission. The attendant global climatic change as a result of increased ambient temperature may, in turn, adversely affect rice cultivation and rice-based production systems. But, rational and judicious optimization of agricultural management practices may result into partial mitigation of the greenhouse effects by curbing CO_2, CH_4 and N_2O emissions to atmosphere during rice cultivation. These management practices, if properly and wisely adopted, would substantially cut down and limit these GHGs emissions from rice and rice-based production systems to atmosphere at the national and global scales. But, the uncertainties in the GHG fluxes from rice fields are due to complexity and variation of the sources, agricultural management practices, limitations in the measurement equipment and the methodology used to quantify the emissions. In order to compile the full GHG balance (for characterization and budgeting) and to understand the processes that affect this balance during rice production, long-term measurements are needed covering all three gaseous species. Hence, close frequency of monitoring/ sampling, proper calibration of monitoring devices and sound precision and accuracy of measurement instruments for quantification of GHGs from rice fields are essential in this regard.

Issues

Global increases in CO_2 concentrations are primarily due to fossil fuel use, with land-use change providing another significant but smaller contribution. Carbon dioxide (CO_2) is released largely from microbial decay of plant litter and soil organic matter. Agriculture through the process of photosynthesis absorb CO_2 from atmosphere, there is very small net emission of CO_2 due to agiculture unless it is done by clearing forest land a kind of practice found in part of India and else where. However, the observed increase in CH_4 concentration is predominantly due to agriculture and fossil fuel use. Methane is produced when organic materials decompose in oxygen-deprived conditions, notably from fermentative digestion by ruminant livestock, from stored manures and from rice grown under flooded conditions. On the other hand, the major source of increase in more than one third in N_2O concentration is due to human activity, primarily agriculture. Nitrus oxide is generated by the microbial transformation of N in soils and manures and nitrogenous fertilizers, and is often enhanced where available N exceeds plant requirements, especially under wet conditions (Oenema et al., 2005). Thus agricultural GHG fluxes are complex and heterogeneous in source and of nature, but the active management of agricultural systems offers possibilities for mitigation.

Agriculture accounted for an estimated emission of 5.1 to 6.1 Gt CO_2-eq year^{-1} in 2005, almost 10-12% of total global anthropogenic emissions of GHGs. Methane contributes 3.3 Gt CO_2-eq year^{-1} and N_2O 2.8 Gt CO_2-eq year^{-1}. Of global anthropogenic GHG emissions in 2005, agriculture accounts for about 60% of N_2O and about 50% of CH_4. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is estimated to be approximately balanced, with CO_2 emissions around 0.04 Gt CO_2 year^{-1} only. Globally, agricultural CH_4 and N_2O emissions have increased by nearly 17% from 1990 to 2005, an average annual emission increase of about 60 Mt CO_2-eq year^{-1}.

The present GHG budget of agricultural fields could be different from previously estimated values because the pattern of land use changed drastically in the last couple of decades. Thus, it becomes evident to detect the current GHG budget from agricultural land. Quantification of GHGs exchanges between terrestrial ecosystems and atmosphere are strongly needed to make comprehensive budgeting of those GHGs. From this point of view, it is pertinent to mention about FLUX NETWORK activities worldwide. AmeriFlux, AsiaFlux, ChinaFlux, KoreaFlux, CARBOEUROPE, NITROEUROPE have been launched on the flux observation project at various types of ecosystems including agricultural fields. Long-term GHG budget monitoring studies are covered under these FLUX NETWORK activities.

Longterm CO_2 measurement data series are continuously being collected and analyzed at the Mauna Loa High Altitude Observatory for about last 50 years (Hofmann et al., 2009). Additionally the Global monitoring Division of the National Oceanic and Atmospheric Administration (NOAA) is also measuring CO_2 and other GHGs in a global network (Conway et al., 2008; Tans, 2011). The United Nations Framework Convention on Climate Change (UNFCCC) records all the GHGs concentrations and sets the global warming potentials of all the naturally/ anthropogenically produced GHGs for a particular time span. There is also a worldwide network of measuring stations promoted by the World Meteorological Organization (WMO) which provides reliable informations. Intergovernmental Panel on Climate Change (IPCC) is the main parent body which publishes the recent and updated concentration of GHGs, their emission scenarios, projected emission trends in the coming future and mitigation options on a periodic interval. Although uncertainty exists regarding the magnitude and flux data of those GHGs worldwide depending on the sources and management practices, which necessitates for proper monitoring and quantification of the trace gas fluxes from different rice production systems.

Rice is grown in the Asian counties during two distinct seasons namely the dry and the wet season. The dry season, from January to April, tends to produce higher yields than the wet season, from July to October. Generally rice thrives in a flooded ecosystem. This condition enriches the nutrients available for crop's growth, allowing farmers to reap abundant harvests. The dark side is that this flooded ecosystem emits mostly CH_4 as well as N_2O depending upon the agricultural management practices that contribute to global climate change. Mid-season drainage or intermittent irrigation, which prevents the development of soil reductive conditions, is considered to be an effective option for mitigating CH_4 emissions from rice fields (Yagi et al 1997). However, under such situations the increased N_2O emissions may offset the benefit gained by reduction of CH_4 emission. There is a trade off between N_2O and CH_4 emission depending upon the water level, level and type of fertilisers applied, soil organic matter and state of residue retention or incorporation. Similarly, for saving water during rice production, alternate wetting and drying (AWD) and growing of aerobic rice in well-drained, nonpuddled and non-saturated soils are becoming popular. But the environmental impacts of these methods are yet to be established. Alternate wetting and drying maintains the basic features of flooded rice fields and keeps the potential for higher production intact. Although this practice reduces CH_4 emissions, it can potentially increase the release of CO_2 and N_2O, two important GHGs. Aerobic rice systems similarly entail drastic changes in C and N emissions and canopy temperature that contribute to global warming and aggravate heat stress for the rice plants. Although the consequences for the sustainability of rice fields remain unknown, it is customary to assess the use of AWD and aerobic rice as an option to mitigate the adverse effects of climate change and, at the same time, to reduce emissions.

Research work should be focused to find out the potential avenues to reduce GHGs emissions from rice production with relatively low opportunity costs and increased productivity.These technologies should be tested and validated in the farmers field. Adapting technologies to local conditions is necessary involving farmers, extension agents and research institutions in technology design and dissemination. Technically, CH_4 reduction from irrigated rice ecologies and CO_2 and N_2O reduction from upland (aerobic) rice production systems could be a promising strategy to mitigate GHG emissions in line with the idea of certified emission reductions (CERs) introduced in the Kyoto Protocol. According to this regulation farmers can receive payments from a private or public institution in an unindustrialized country for reducing GHG emissions in line with the idea of Carbon Credit Compliance. In the next step, a designated panel of the UNFCCC can approve CERs that can be used by the purchasing institution as part of its required contingent of emission savings. Increasing food production is an absolute necessity for ever increasing human population and improved resource use efficiencies are imperative to achieving this goal. Therefore, definite provisions should be there for adopting CERs in different rice production systems keeping in mind the food security and GHG mitigation by computing net GWP savings based on food production targets.

Monitoring technologies for study of greenhouse gas emissions from rice fields

Flooded rice paddies and aerobic rice production systems have important roles on GHG budget. The rice crops uptake atmospheric CO_2 due to photosynthesis and the soil microorganisms along with crop emit CO_2 during respiration. Lowland submerged rice paddies are major CH_4 source and upland conditions enriched with nitrogenous fertilizers mostly emits N_2O and CO_2. These sink/source strength capacity depends on the management practices. Therefore, GHG emissions from rice fields of different rice production systems demands continuous, precise and accurate monitoring and their proper quantification for budgeting. Thus long-term GHGs flux observation studies in different rice ecosystems are necessary. Several technologies are available for monitoring of GHG emission from agriculture. Real time accurate and precise monitoring of GHGs emissions from rice paddy ecosystems are possible with the help of open and or closed path eddy covariance (EC) technique, static chambers method and by soil and plant canopy chambers using infrared gas analyzer (IRGA).

Numerous micrometeorological measurements of CO_2 flux have been made in paddy fields since the 1960s, and the eddy covariance method was often applied after the 1980s (Miyata et al., 2000). However, most of those studies involved short-term measurements lasting a few days to a few weeks. A long-term CO_2 flux measurement study covering two consecutive growing seasons at a rice field in Texas, USA, using the relaxed eddy accumulation method. However, as mentioned before, differences in cultivation practices and field management affect the CO_2 budgets of paddy fields.

Trace gas fluxes can be measured using chamber or micrometeorological methods (Wesely & Hicks, 2000). Chamber methods integrate over small areas, from < 1 m^2 (Husted, 1993) up to 64 m^2 (Galle et al., 1994) and can alter local environmental conditions. General errors caused by chambers are related to perturbations of the natural conditions at the sampling site, modifications of the microclimate, pressure-induced gas flows in open chambers and inhibiting effects of concentration build-up in closed chambers (Lapitan et al., 1999). On the other hand, micrometeorological methods do not interfere with processes of gas exchange between the surface source and the atmosphere and are ideally suited for continuous flux measurements (Denmead, 1995).

Eddy covariance systems using tunable diode laser absorption spectroscopy are now becoming available for automated measurement of CH_4 and N_2O fluxes from agriculture (Kim et al., 1999). However, these systems are costly. In contrast, combining profile measurements of CH_4 concentrations with eddy covariance measurements of energy fluxes (denoted as flux-gradient method) (Miyata et al., 2000) is less costly than the laser based spectroscopy method for the measurement of CH_4. In contrast to the conventional chamber technique (Khalil et al., 2008), the flux-gradient method can measure the CH_4 flux without physically disturbing the sample area. There have been several attempts to use measured CH_4 effluxes at specific sites to arrive at estimates for the global emission from rice paddies. The results vary greatly, from 20 to 100 Tg yr^{-1} (Zou et al., 2005). Field experiments have shown that the large variability in CH_4 emissions is both spatial and temporal as well as seasonal and diurnal (Sass et al., 1991). Although a large number of field measurements of CH_4 effluxes have been made in the past decade, their spatial coverage is still poor, and extrapolating the results from point measurements to the global scale involves many uncertainties (Cao et al., 1995).

FIGURE 1. *Eddy covariance system*

Eddy covariance technique-based net ecosystem carbon dioxide exchange

Long term measurements of CO_2 flux have been carried out in various ecosystems in the world, especially in forest ecosystems as they are believed to be the most influential terrestrial ecosystems in the global CO_2 budget (Carrara et al., 2003). On the other hand, non-forest ecosystems *viz.* grasslands, wetlands and agricultural fields have also been observed because they contribute to regional and global CO_2 budgets (Tsai et al., 2006). The eddy covariance (EC) technique is widely employed as the standard micrometeorological method to monitor fluxes of CO_2, water vapour and heat, which are bases to determine CO_2 and heat balances of land surfaces (Fig. 1) (Aubinet et al., 2000). The EC technique has become the most important method for measuring trace gas exchange between terrestrial ecosystems and the atmosphere (Smith et al., 2010). The direct, continuous measurement of carbon, water and energy fluxes between vegetated canopies or biosphere and the atmosphere can be obtained with minimal disturbance to the vegetation using this sophisticated research tool. It can represent a large area of land at the ecosystem than the typical plot area (Lalrammawia et al., 2010) for a short period or even for several years. It has become the backbone for bottom up estimates of continental carbon balance from hourly to inter annual time scales (Reichstein et al., 2005).

The EC technique is based on high frequency (10-20 Hz) measurements of wind speed and direction as well as CO_2 and water concentrations at a point over the canopy using a three-axis sonic anemometer and a fast response infrared gas analyzer (Fig. 2) (Aubinet et al., 2003). Assuming perfect turbulent mixing, these measurements are typically integrated over periods of half an hour building the basis to calculate carbon and water balances from daily to annual time scales. Apart from three-axis sonic anemometer and fast response infra-red gas analyzer several other sensors are attached to the EC unit for measurement of some auxiliary parameters namely, relative humidity, air temperature, incoming radiation, net radiation, photosynthetic photon flux density, photosynthetically active radiation, precipitation, soil temperature, soil moisture, soil heat flux etc. Eddy covariance flux towers are currently operational worldwide covering different climate conditions; land use and land cover (Baldocchi et al., 2001).

FIGURE 2. *Sensors of eddy covariance system*

In Asia, EC flux measurements were conducted in Japan (Miyata et al., 2005;), Korea (Moon et al., 2003), Bangladesh (Hossen et al., 2011), Philippines (Alberto et al., 2009), Thailand (Pakoktom et al., 2009), China (Xiu E et al., 2007), Taiwan (Tseng et al., 2010) and India (Bhattacharyya et. al., 2011) to monitor seasonal, annual and or inter-annual variations in CO_2 fluxes in rice fields (Fig. 3). In rice paddy ecosystems it can be employed to measure net ecosystem CO_2 exchange (NEE) or net ecosystem production (NEP). The technique uses the covariance between rapid fluctuations in vertical wind speed measured with a three-dimensional ultrasonic anemometer and simultaneous measurements of the rapid fluctuations in the CO_2 concentration as measured by a fast-response IRGA. A positive covariance between vertical fluctuations and the CO_2 mixing ratio indicates the net CO_2 transfer into the atmosphere from plant-soil system and a negative value indicates net CO_2 absorption by the vegetation (Moncrieff et. al., 1997). Net ecosystem exchange is measured continuously by EC technique applying proper correction terms and gap-filling, if required. Net ecosystem exchange is further partitioned into gross primary production (GPP) and ecosystem respiration (RE). Ecosystem respiration is extrapolated from night time fluxes to daytime by using temperature response functions and afterwards GPP is calculated by subtracting RE from NEE (Fig.4) (Bhattacharyya et. al. 2011).

FIGURE 3. *Eddy covariance system in rice field*

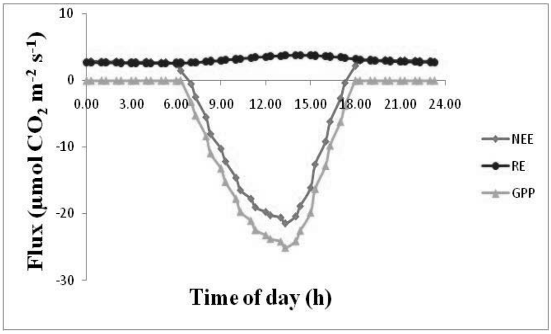


FIGURE 4. *Net ecosystem exchange, gross primary production and ecosystem respiration of rice field in Cuttack*

Eddy covariance system continuously monitors and stores half-hourly and hourly CO_2 flux (NEE) data, using which carbon footprint analysis of specific ecosystem can be characterized precisely. As because plants exchange most of their carbon as CO_2, eddy flux-derived NEP is an ideal variable for C budgeting from local to regional scales. However, over time, net C fluxes are good proxies for ecosystem total biomass stock change (Baldocchi, 2003). The flux networks use eddy covariance-based measurement system for assessing regional sectoral carbon budgets. There are hundreds of eddy covariance towers monitoring continuously and organized in global network including forests, grasslands and croplands (Smith et al., 2010).

FIGURE 5. *Soil respiration chamber in rice field*

FIGURE 6. *Soil respiration chamber and temperature sensor placed on soil*

Measurement of soil carbon dioxide efflux and plant respiration by infra-red gas analyzer-based soil respiration chamber or canopy chamber

Infra-red gas analyzer -based field measurement is the most widely used technique for assessing soil respiration flux rates (Fig. 5 & 6). The method (for measuring soil CO_2 efflux employing IRGA) estimates the increase in enclosed chamber CO_2 concentration over a specified time (Luo & Zhou, 2006). Different IRGA-based measurements of soil respiration or soil CO_2 efflux depends on differences in IRGA and chamber design (cuvette area and volume, use of collars, presence or absence of chamber vents), measurement parameters (enclosure time, chamber flow rate, purge parameters) and CO_2-flux algorithms (with or without moisture and temperature correction). These effects are also dependent on soil type and vegetation in which the measurements are being undertaken (Mills et al., 2011). Moreover, the chambers always affect the object being measured, with each chamber type having its own limitations (Davidson et al., 2002).

The three major chamber techniques used widely for measuring soil CO_2 efflux are closed static chamber (non-steady-state non-through-flow chamber), closed (non-steady-state through-flow chamber) and open dynamic chamber (steady-state through-flow chamber). In case of non-steady-state chambers (both the through-flow and non-through-flow types) the CO_2 efflux is determined from the rate of concentration increase in an isolated chamber, which has been placed on the soil surface for a known period of time. In case of steady-state chambers CO_2 efflux is calculated from the difference between CO_2 concentration at the inlet and the outlet of the chamber.

When a non-steady-state chamber is placed on the soil and the concentration in the chamber headspace starts to change, rising concentration within the chamber may influence the CO_2 efflux from the soil by altering the natural soil concentration gradient (Livingston & Hutchinson, 1995). Pressure anomalies caused by placing the chamber on the soil surface may also disturb the CO_2 concentration gradient in the soil. In case of steady-state chambers, pressure differences between the inside and outside of the chamber can generate mass flow of CO_2 from the soil into the chamber (Lund et al., 1999).

In a dynamic open chamber method, air passes through the chamber and gas analyser and is then evacuated; the efflux of CO_2 from the soil (Sr) covered by the chamber is obtained as a function of the difference in CO_2 concentration between air entering and leaving the chamber (Eq. 1) (Smith et al., 2008).

$$Sr = \Delta c\,(f / A) \text{ -------- } 1$$

Where, c is the difference in CO_2 mass fraction in the incoming and outgoing air streams; f is the gas flow rate through the chamber and A is the surface area covered by the chamber (Nakayama, 1990). The difference in CO_2 concentration is usually measured by an IRGA.

If a closed chamber is placed on the soil, the concentration of CO_2 respired from the soil will build up inside the chamber and this enrichment can be used to estimate the efflux from the soil. This method is the basis of many of the successful commercial designs in the market today. The soil efflux can be expressed by (Eq. 2):

$Sr = (\Delta c / \Delta t) V / A$ -------- 2

Where, c is the CO_2 concentration increment in the chamber in the time interval t; V is the volume of air within the chamber and A is the soil surface area covered by the chamber. The CO_2 content of a sample taken at discrete intervals can be measured by alkali absorption or by gas chromatography (GC) (Castro et al., 1994).

Plant respiration in case of rice is measured by the canopy chamber, enclosing the canopy and stand for specified time and then measuring the liberated CO_2 due to respiration with the help of IRGA.

Measurement of emission of methane and nitrous oxide fluxes by chamber and eddy covariance method

Methane and N_2O emissions are measured through the manual or automatic closed chamber measurements and or employing eddy covariance technique. These chamber measurements are widely used as they are easy to apply in field trials with multiple small plots. The manual chamber measurements (Fig. 7) are usually made very frequently (2-3 days interval) where as automatic chamber measurements allow continuous and frequent measurements.

FIGURE 7. *Chamber measurement for methane and nitrous oxide emission studies*

From the static chambers (equipped with small pulse pump for homogeneous mixing of air sample inside the chamber over specific time period) air samples are collected in tedlar® bags at 0, 15 and 30 minute intervals. Samples are then collected by syringe for analysis of CH_4 and N_2O by gas chromatography using flame ionisation and electron capture detectors, respectively (Das et al., 2011).

Automated chamber methods are expected to produce more reliable results rather than manual chamber measurements as diurnal variations in fluxes of GHGs (CH_4, N_2O) are captured. Automatic chamber measurements may suffer from underestimation of fluxes due to chamber effects on soil moisture conditions during rainfall (Yao et al., 2009).

An integrated eddy covariance system associated with trace gas analyzer (TGA), a tunable diode laser analyzer, can measure trace gas fluxes *viz*. CH_4, N_2O, NO_2, NH_3 and CO_2. Laser spectroscopy also provides new measurement techniques to measure CH_4 and N_2O concentrations at high temporal resolution (10 Hz), appropriate for eddy covariance flux calculations (Hendriks et al., 2008). Eddy covariance measurements of CH_4 and N_2O using lead salt tunable diode laser (TDL) spectrometers and quantum cascade laser (QCL) spectrometers are also possible (Neftel et al., 2007).

In spite of considerable efforts to quantify CH_4 and N_2O emissions from rice fields, the estimates of this source strength are still attached to major uncertainties. Intensive field measurement campaigns have clearly revealed the complex interaction of water regime as the major determinant of emissions on the one hand and several other influencing factors on the other. Given the diversity of rice production systems, reliable upscaling of CH_4 and N_2O source strengths requires a high degree of differentiation in terms of management practices and natural factors. Modeling approaches have been developed to simulate their emissions as a function of a large number of input parameters, namely, modalities of management as soil and climate parameters.

Budgeting

Agriculture accounts for about 15% of the global emission of GHGs. Carbon dioxide, CH_4 and N_2O budget in rice fields are affected by structure and dynamics of anaerobic and aerobic conditions in the soil and due to other agricultural management practices. Methane emission increases under continuous flooding while N_2O is primarily emitted in pulses after fertilization and strong rainfall events. Various rice growing environments show wide spatio-temporal variability in CH_4 emission. Land use practices and N-fertilizer applications greatly influence N_2O emission from soil.

Carbon dioxide flux exhibited a clear diurnal pattern ranging from -38 to 10 µmol CO_2 m^{-2} s^{-1} during full heading stage of rice (70-79 Days after transplanting) in 2006 boro rice growing season in Bangladesh (Hossen et al., 2007). The total C budget integrated over the cropping period showed that the net ecosystem CO_2 exchange (NEE) in flooded rice fields (-258 g C m^{-2}) was about three times higher than that of aerobic rice fields (-85 g C m^{-2}) in IRRI, Philippines (Alberto et al., 2009). The daily CO_2 flux values in rice ecosystem in Taiwan ranged from -17.03 µmol CO_2 m^{-2} s^{-1} to 12.85 µmol CO_2 m^{-2} s^{-1}. Fluxes of CO_2 were always positive during night hours, average value being 2.76 µmol CO_2 m^{-2} s^{-1}; whereas during the daytime the flux was found to be negative with an average value of -1.22 µmol CO_2 m^{-2} s^{-1} (Tseng et al., 2010). Spatial and temporal variation of CO_2 fluxes were seen in different Asian countries (Table 1).

TABLE 1. *Comparison of mean carbon dioxide fluxes measured by eddy covariance system in Asian countries.*

Location	CO_2 flux (µmol m^{-2} s^{-1})	Fertilizer and water management	Duration
Japan (day/night) (Miyata et al., 2000)	-3.81 (-16.95/9.32)	Chemical fertilization and drained soil condition	1-week (a month before heading stage of the crop)
Japan (day/night) (Miyata et al., 2000)	-7.63 (-19.57/4.32)	Chemical fertilization and flooded soil condition	1-week (a month before heading stage of the crop)
Taiwan (day/night) (Tseng et al., 2010)	0.71 (-1.22/2.76)	Chemical fertilization and drained soil condition	1-month (from heading to maturity stage of the crop)

Methane emission varied from 14 to 375 mg m^{-2} d^{-1} in most rice growing areas in the world. Annual global estimation of CH_4 emission from flooded rice fields accounted for 7.08 Tg based on the biomass (Sinha, 1995). In Thailand, Wassmann et al. (2000) estimated 99 Kg CH_4 ha^{-1} $season^{-1}$ from deepwater rice fields. Average CH_4 emission rates ranged from 11-364 mg m^{-2} d^{-1} from rice fields of Beijing, China (Wang et al., 2000). It is affected by water regimes, soil amendments, cultivars and type of fertilizers used. In India the mean CH_4 emission from rice fields ranged between 3.5-4.2 Tg yr^{-1} (Parashar et al., 1996). An irrigated continuously flooded rice paddy system showed a CH_4 emission value of 4-26 mg m^{-2} h^{-1} and 0.7-4.7 Gg ha^{-1} per cropping season of 75 days (Adhya et al., 1994). Bhatia et al. (2004) estimated 4.7 Tg yr^{-1} CH_4 emission from the Indian paddy fields with the highest emission of 1.379 Tg yr^{-1} from the irrigated rice fields. Methane emission from lowland rice preceded by an upland crop in dry season was 12.52-13.09 g CH_4 m^{-2} day^{-1}, which was significantly lower than the CH_4 emission from a lowland rice-rice system (Adhya et al., 2000a). Adhya et al. (2000b) reported an average emission of 32 Kg CH_4 ha^{-1} yr^{-1} from a rainfed tropical rice ecosystem.

The tentative global estimate of N_2O emission from agricultural land is 2.3-3.7 Tg N yr^{-1} (Bouwman, 1990). Chao et al. (2000) estimated around 0.67 Mg N_2O-N yr^{-1} from the paddy fields of Taiwan. N_2O emission from the Chinese rice fields ranged from 39-164 mg N m^{-2} hr^{-1} (Chen et al., 1997). Agriculture related activities account for around 90% of the total N_2O emissions in India (Garg et al., 2001). Parashar et al. (1998) estimated the total N_2O emission from Indian paddy and wheat fields were 199-279 Gg per annum. Sharma et al. (1995) estimated N_2O emissions from irrigated and upland paddy fields of India at 4-210 and 2-10 Gg yr^{-1}, respectively. Nitrous oxide emission from Indian agricultural field was estimated to be 0.08 Tg annually (Bhatia et al., 2004). The irrigated rice-wheat system is a significant source of N_2O, emitting around 15 kg N_2O-N ha^{-1} yr^{-1} (Aulakh et al., 2001).

The Denitrification and Decomposition (DNDC) model was applied for estimation of GHG emissions from rice fields in India using a compiled soil - climate - land use database. Continuous flooding of rice fields (42.25 million ha) resulted in annual net emissions of 1.07–1.10, 0.04–0.05 and 21.16–60.96 Tg of CH_4-C, N_2O-N and CO_2-C, respectively, with a cumulated GWP of 130.93–272.83 Tg CO_2 equivalent. Intermittent flooding of rice fields reduced annual net emissions to 0.12–0.13 Tg CH_4-C and 16.66–48.80 Tg CO_2-C while N_2O emission increased to 0.05–0.06 Tg N_2O-N. The GWP, however, reduced to 91.73–211.80 Tg CO_2 equivalent (Pathak et al., 2005).

Conclusions

Greenhouse gas fluxes in terms of gaseous carbon and nitrogen between rice fields and the atmosphere are controlled by several biological and physical processes. The trace gas flux dynamics during rice cultivation follows complex pathways and shows variability at different time scales starting from diurnal variation to seasonal, annual and interannual variations. As many of the factors controlling gas exchange between rice paddies and atmosphere are different from other ecosystems, field studies should be designed to measure net fluxes and to improve understanding of the factors including detailed mechanisms controlling the fluxes in different rice production systems. Therefore, quantification of net fluxes of gaseous-C, in forms of CO_2-C and CH_4-C, and gaseous-N in the form of N_2O-N exchanged between the rice fields and atmosphere is required for quantification of those GHGs and to determine their impact on vegetation and on environment. The continuous monitoring and measurement would provide a useful understanding for examining the roles of different parts of rice and rice-based cropping systems contributing to GHG fluxes under different agro-climatic zones and management practices. This could be further calibrated, up scaled and validated by ecosystem modelling approach. The study can also be employed to explore better understanding of GHG exchanges with the help of remote sensing software applications for scaling up gaseous-C and N fluxes from point scale and it can further be extrapolated to upscale for predicting future anticipated climate changes. Therefore, research approaches are needed for enhancing knowledge and better understanding on the processes involved in gaseous carbon and nitrogen emissions in different agro-environments. The eddy covariance technique measures directly the net ecosystem CO_2 exchange for characterization of carbon budget in terrestrial ecosystems. This device when coupled with other accessory sensors and trace gas analyzers can measure also CH_4 as well as N_2O fluxes from rice fields. The trace gas flux dynamics during rice cultivation follows complex pathways and shows variability at different time scales starting from diurnal variation to seasonal, annual and interannual variations. Thus EC method along with IRGA-based soil and plant (canopy) respiration chamber and manual/ automatic chamber measurement of CH_4 and N_2O, can employ new methodologies that account for all components of GHG fluxes required for accurate quantification of trace gas exchange at the landscape level with regard to rice production. Moreover, this integrated measurement approach would provide a useful tool for examining the roles of different parts of rice ecosystem contributing to GHG fluxes in different rice production systems under different agro-climatic zones and management practices. The flux data of GHGs along with other climate parameters can be interpreted in a better way and tested via models that incorporate all biogenic greenhouse gases. These high-resolution process-based models can be applied to upscale and validate GHG emissions from any point and can be extrapolated to higher scales for predicting future anticipated climate changes. Impact of GHGs on climatic conditions and the influence of such climatic change on rice productivity is now reality, although there is a need to assess the extent of such influences.

References

Adhya, T.K., Bharati, K., Mohanty, S.R., Mishra, S.R., Rao, V.R., Sethunathan, N., & Wassmann, R. (2000a). Methane emission from rice fields at Cuttack, India. *Nutrient Cycling in Agroecosystems,* 58, 95-105.

Adhya, T.K., Mishra, S.R., Rath, A.K., Bharati, K., Mohanty, S.R., Ramakrishnan, B., Rao, V.R., & Sethunathan, N. (2000b). Methane efflux from rice-based cropping system under humid tropical conditions of eastern India. *Agriculture Ecosystems and Environment,* 79, 85-90.

Adhya, T.K., Rath, A.K., Gupta, P.K., Rao, V.R., Das, S.N., Parida, K., Parashar, D.C., & Sethunathan, N. (1994). Methane emission from flooded rice fields under irrigated conditions. *Biology and Fertility of Soils,* 12, 245-248.

Alberto, R., Carmelita, Ma., Wassmann, R., Hirano, T., Miyata, A., Kumar, A., Padre, A., & Amante, M. (2009). CO_2/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the Philippines. *Agricultural and Forest Meteorology,* 149, 1737-1750.

Artus, F., Chamard, P., Piacentino, S., Sferlazzo, D.M., De Silverstri, L., di Sarra, A., Meloni, E., & Monteleone, F. (2009). Influence of transport and trends in atmospheric CO_2 at Lampedusa. *Atmospheric Environment,* 43, 3044-3051.

Aubinet, M., Clement, R., Elbers, J.A., Foken, T., Grelle, A., Ibrom, A., Moncrieff, J., Pilegaard, K., Rannik, U., & Rebmann, C. (2003). Methodology for data acquisition, storage and treatment. In R. Valentini (Ed.), *Fluxes of carbon, water and energy of European forests*. Berlin: Springer-Verlag.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C.H., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., & Vesala, T. (2000). Estimates of the annual net carbon and water exchange of forests: The EUROFLUX Methodology. *Advances in Ecological Research,* 102, 113-175.

Aulakh, M.S., Khera, T.S., Doran, J.W., & Bronson, K. (2001). Denitrification, N_2O and CO_2 fluxes in rice-wheat cropping systems as affected by crop residues, fertilizer N and legume green manure. *Biology and fertility of soils,* 34, 375-389.

Baldocchi, D., Falge, E., Gu, L., Olsan, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Katul, G., Fuentes, J., Goldstein, A., Law, B., Lee, X., Mali, Y., Meyers, T., Munger, W., Occhel, W., Paw, K.T., Pilegaaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson. K., & Wofsy, S. (2001). FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bulletin of American Meteorological Society,* 82, 2415-2434.

Baldocchi, D.D. (2003). Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystem: Past, present and future. *Global Change Biology,* 9, 479-492.

Bhattacharyya, P., Rao, K.S., & Adhya, T.K. (2011). Advanced technologies for greenhouse gas monitoring in rice and rice-based cropping systems. *CRRI, Research/Technical Brief-01*; pp-4, Cuttack, India: CRRI.

Bhatia, A., Pathak, H., & Aggarwal, P.K. (2004). Inventory of methane and nitrous oxide emissions from agriculture soils of India and their global warming potential. *Current Science,* 87, 317-324.

Bouwman, A.F. (1990). Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In A.F. Bouwman (Ed.), *Soil and greenhouse effect*. (pp. 61-127). New York: John Wiley & Sons.

Bronson, K.F., Neue, H.U., Singh, U., & Abao, Jr.E.B. (1997). Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil. I. Residue, nitrogen, and water management. *Soil Science Society of American Journal,* 61, 981-987.

Cao, M.K., Dent, J.B., & Heal, O.W. (1995). Methane emissions form China's paddy land. *Agriculture Ecosystems and Environment,* 55, 129-137.

Carrara, A., Kowalsk, A.S., Neirynck, J., Janssens, I.A., Yuste, J.C., & Ceulemans, R. (2003). Net ecosystem CO_2 exchange of mixed forest in Belgium over 5 years. *Agricultural and Forest Meteorology,* 119, 209-227.

Castro, M.S., Peterjohn, W.T., Melillo, J.M., Steudler, P.A., Gholz, H.L., & Lewis, D. (1994). Effects of nitrogen fertilization on the fluxes of N_2O, CH_4 and CO_2 from soils in a Florida slash pine plantation. *Canadian Journal of Forest Research,* 24, 9-13.

Chao, C.C., Young, C.C., Wang, Y.P., & Chao, W.L. (2000). Daily and seasonal nitrous oxide fluxes in soils from hardwood forest and different agroecosystems of Taiwan. *Chemosphere Global Change Science,* 2, 77-84.

Chen, J., Xuan, J., Du, C., & Xie, J. (1997). Effect of potassium nutrition of rice on rhizosphere redox status. *Plant and Soil,* 188, 131-137.

Conway, T.J., Lang, P.M., & Masarie, K.A. (2008). Atmospheric carbon dioxide dry air mole fractions from the NOAA ESRL Carbon Cycle Cooperative Global Air Sampling Network, 1968-2007 (2008-07-24). Available at ftp://ftp.cmdl.noaa.gov/ccg/co2/flask/ event/.

Das, S., Ghosh, A., & Adhya, T.K. (2011). Nitrous oxide and methane emission from a flooded rice field as influenced by separate and combined application of herbicides bensulfuron methyl and pretilachlor. *Chemosphere,* 84, 54-62.

Davidson, E.A., Savage, K., Verchot, L.V., & Navarro, R. (2002). Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agricultural and Forest Meteorology,* 113, 21-37.

Denmead, O.T. (1995). Novel meteorological methods for measuring trace gas fluxes. *Philosophical Transactions of the Royal Society*: *Physical Engineering Sciences,* 351, 383-396.

Galle, B., Klemedtsson, L., & Griffith, D.W.T. (1994). Application of a Fourier transform IR system for measurements of N_2O fluxes using micrometeorological methods, an ultralarge chamber system, and conventional field chambers. *Journal of Geophysical Research,* 99(D8), 16575-16583.

Garg, A., Bhattacharya, S., Shukla, P.R., & Dadwal, V.K. (2001). Regional and sectoral assessment of greenhouse gas emission in India. *Atmospheric Environment,* 35, 2679-2695.

Guerra, L.C., Bhuiyan, S.I., Toung, T.P., & Barker, R. (1998). Producing more rice with less water. International Water Management Institute, *SWIM Paper 5*, pp. 24.

Haszpra, L., Bareza, Z., Hidy, D., Szilagyi, I., Dlugokencky, E., & Tans, P. (2008). Trends and temporal variations of major greenhouse gases at a rural site in Central Europe. *Atmospheric Environment,* 42, 8707-8716.

Hendriks, D.M.D., Dolman, A.J., Van der Molen, M.K., & Van Huissteden, J. (2008). A compact and stable eddy covariance set-up for methane measurements using off-axis integrated cavity output spectroscopy. *Atmospheric Chemistry and Physics,* 8, 1-13.

Hofmann, D.J., Butler, J.H., & Tans, P.P. (2009). A new look at atmospheric carbon dioxide. *Atmospheric Environment,* 43, 2084-2086.

Hossen, M.S., Mano, M., Miyata, A., Baten, M.A., & Hiyama, T. (2011). Seasonality of ecosystem respiration in a double-cropping paddy field in Bangladesh. *Biogeosciences Discussion,* 8, 8693-8721.

Husted, S. (1993). An open chamber technique for determination of methane emission from stored livestock manure. *Atmospheric Environment,* 27, 1635-1642.

Intergovernmental Panel on Climate Change (IPCC). 2001. *Climate change - The scientific basis*. Cambridge Univ., UK: Cambridge Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change - The scientific basis*. Cambridge Univ., UK: Cambridge Press.

Jianwen, Z., Yao, H., Xunhua, Z., Yuesi, W., & Yuquan, C. (2004). Static opaque chamber-based technique for determination of net exchange of CO_2 between terrestrial ecosystem and atmosphere. *Agricultural and Forest Meteorology*, 4, 381-388.

Khalil, M.A.K., Shearer, M.J., Rasmussen, R.A., Changlin, D., & Ren Lixin. (2008). Production, oxidation and emissions of methane from rice fields in China. *Journal of Geophysical Research*, 113, G00A04, 12.

Kim, J., Verma, S.B., & Billesbach, D.P. (1999). Seasonal variation in methane emission from a temperate phragmites-dominated marsh: Effect of growth stage and plant-mediated transport. *Global Change Biology*, 5, 433-440.

Kirk, G. J. D., & Olk, D.C. (2000). *Carbon and nitrogen dynamics in flooded soils*. Manila, Philippines: International Rice Research Institute.

Lalrammawia, C., & Paliwal, K. (2010). Seasonal changes in net ecosystem exchange of CO_2 and respiration of *Cenchrus ciliaris* L. grassland ecosystem in semi-arid tropics: An eddy covariance measurement. *Current Science*, 98, 1211-1218.

Lapitan, R.L., Wanninkhof, R., & Mosier, A.R. (1999). Methods for stable gas flux determination in aquatic and terrestrial systems. In A.F. Bouwman (Ed.), *Approaches to scaling of trace gas fluxes in ecosystems. Developments in atmospheric science 24.* (pp. 27-66). Amsterdam: Elsevier.

Livingston, G.P., & Hutchinson, G.L. (1995). Enclosure-based measurement of trace gas exchange: Applications and sources of error. In P.A. Matson, R.C. Harriss (Eds.), *Biogenic trace gases: Measuring emissions from soil and water*. (pp. 14-50). Cambridge: Blackwell Science.

Lund, C.P., Riley, W.J., Pierce, L.L., & Field, C.B. (1999). The effects of chamber pressurization on soil-surface CO_2 flux and the implications for NEE measurements under elevated CO_2. *Global Change Biology*, 5, 269-281.

Luo, Y., & Zhou, X. (2006). *Soil respiration and the environment*. London: Academic Press.

Mills, R., Glanville, H., McGovern, S., & Emmett, B. (2011). Soil respiration across three contrasting ecosystem types: Comparison of two portable IRGA systems. *Agricultural and Forest Meteorology*, 174, 532-535.

Miyata, A., Iwata, T., Nagai, H., Yamada, T., Yoshikoshi, H., Mano, M., Ono, K., Han, G.H., Harazano, Y., Ohtaki, E., Baten, M.A., Inohara, S., Takimoto, T., & Saito, M. (2005). Seasonal variation of carbon dioxide and methane fluxes at single cropping paddy fields in central and western Japan. *Phyton (Austria)*, 45, 89-97.

Miyata, A., Leuning, R., Denmead, O.W., Kim, J., & Harazano, Y. (2000). Carbon dioxide and methane fluxes from an intermittently flooded paddy field. *Agricultural and Forest Meteorology*, 102, 287-303.

Moncrieff, J.B., Massheder, J.M., Verhoef, A., Elbers, J., Heutsunkveld, B.H., Scott, S., deBruin, H., Kabat, P., Soegaard, H., & Jarvis, P.G. (1997). A system to measure surface fluxes of energy, momentum and carbon dioxide. *Journal of Hydrology*, 188-189, 589-611.

Moon, B.K., Hong, J., Lee, B.R., Yun, J.I., Park, E.W., & Kim, J. (2003). CO_2 and energy exchange in rice paddy for the growing season of 2002 in Hari, Korea. *Korean Journal of Agricultural and Forest Meteorology*, 5, 51-60.

Nakayama, F.S. (1990). Soil respiration. *Remote Sensing Reviews*, 5, 311-321.

Neftel, A., Flechard, C., Ammann, C., Conen, F., Emmenegger, L., & Zeyer, K. (2007). Experimental assessment of N_2O background fluxes in grassland systems. *Tellus*, 59(B), 470-482.

Neue, H.U. (1993). Methane emission from rice fields. *Bioscience*, 43, 466-474.

Oenema, O., Wrage, N., Velthof, G.L., van Groenigen, J.W., Dolfing, J., & Kuikman, P.J. (2005). Trends in global nitrous oxide emissions from animal production systems. *Nutrient Cycling in Agroecosystem,* 72, 51-65.

Olk, D.C., Cassman, K.G., Mahieu, N., & Randall, E.W. (1998). Conserved chemical properties of young humic acid fractions in tropical lowland soil under intensive irrigated rice cropping. *European Journal of Soil Science,* 49, 337-349.

Pakoktom, T., Aoki, M., Kasemsap, P., Boonyawat, S., & Attarod, P. (2009). CO_2 and H_2O fluxes ratio in paddy fields of Thailand and Japan. *Hydrological Research Letters,* 3, 10-13.

Pan, G., Li, L., Wu, L., & Zhang, X. (2003). Storage and sequestration potential of topsoil organic carbon in China's paddy soils. *Global Change Biology,* 10, 79-92.

Parashar, D.C., Kulashrestha, U.C., & Sharma, C. (1998). Anthropogenic emissions of NO_x, NH_3 and N_2O in India. *Nutrient Cycling in Agroecosystem,* 52, 255-259.

Parashar, D.C., Mitra, A.P., Gupta, P.K., Rai, J., Sharma, R.C., Singh, N., Kaul, S., Lal, G., Chaudhay, A., Ray, H.S., Das, S.N., Parida, K.M., Rao, S.B., Kanungo, S.P., Ramasami, T., Nair, B.U., Swamy, M., Singh, G., Gupta, S.K., Singh, A.R., Saikia, B.K., Barua, A.K.S., Pathak, M.G., Iyar, C.P.S., Gopalkrishnan, M., Sane, P.V., Singh, S.N., Banerjee, R., Sethunathan, N., Adhya, T.K., Rao, V.R., Palit, P., Saha, A.K., Purkait, N.N., Chaturvedi, G.S., Sen, S.P., Sen, M., Sarkar, B., Banik, A., Subbaraya, B.H., Lal, S., Venkataramani, S., & Sinha, S.K. (1996). Methane budget from paddy fields in India. *Chemosphere,* 33, 737-757.

Pathak, H., Li, C., & Wassmann, R. (2005). Greenhouse gas emissions from Indian rice fields: Calibration and upscaling using the DNDC model. *Biogeosciences,* 1, 1-11.

Ramonet, M., Ciais, P., Aalto, T., Aulagnier, C., Chevalier, F., Cipriano, D., Conway, T.J., Haszpra, L., Kazan, V., Meinhardt, F., Paris, J.D., Schmidt, M., Simmonds, P., Xueref-Remy, I., & Necki, J. (2010). A recent buildup of atmospheric CO_2 over Europe. Part I: Observed signals and possible explanations. *Tellus,* 62(B), 1-13.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmaov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., & Valentini, R. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm. *Global Change Biology,* 11, 1424-1439.

Sass, R.L., Fisher, F.M., Tuner, F.T., & Jund, M.F. (1991). Methane emission from rice fields as influenced by solar radiation, temperature and straw incorporation. *Global Biochem*ical *Cycles,* 5, 335-350.

Sharma, C., Gupta, P.K., & Parashar, D.C. (1995). Nitrous oxide estimates from paddy fields and forests in India. *Indian Journal of Radio Space Physics*, 24, 311–313.

Sinha, S.K. (1995). Global methane emission from rice paddies: Excellent methodology but poor extrapolation. *Current Science,* 68, 643-646.

Smith, P., Fang, C., Dawson, J.J.C., & Moncreiff, J. (2008). Impact of global warming on soil organic carbon. *Advances in Agronomy,* 97, 1-43.

Smith, P., Lanigan, G., Kutsch, W.L., Buchmann, N., Eugster, W., Aubinet, M., Ceschia, E., Beziat, P., Yeluripati, J.B., Osborne, B., Moors, E.J., Brut, A., Wattenbach, M., Saunders, M., & Jones, M. (2010). Measurements necessary for assessing the net ecosystem carbon budget of crop lands. *Agriculture Ecosystems and Environment,* 139, 302-315

Tans, P. (2011). NOAA/ESRL. Available at http://www.esrl.noaa.gov/gmd/ccgg/trends.

Tsai, J.L., Tsuang, B.J., Lu, P.S., Yao, M.H., & Hsieh, H.Y. (2006). Surface energy components, CO_2 flux and canopy resistance from rice paddy in Taiwan. In 17th symposium on boundary layers and turbulence, 27th conference on agricultural and meteorology, and the 17th conference on biometeorology and aerobiology. pp.21-25. San Deigo, CA, USA.

Tseng, H.K., Tsai, L.J., Alagesan, A., Tsuang, J.B., Yao, H.M., & Kuo, H.P. (2010). Determination of methane and carbon dioxide fluxes during the rice maturity period in Taiwan by combining profile and eddy covariance measurements. *Agricultural and Forest Meteorology,* 150, 852-859.

Vinogradova, A., Fedorova, E., Belikov, I., Ginzburg, A., Elansky, N., & Skorokhod, A. (2007). Temporal variations in carbon dioxide and methane concentrations under urban conditions. *Izvestiya Atmospheric and Oceanic Physics,* 43, 599-611.

Wang, Z.Y., Xu, Y.C., Li, Z., Guo, Y.X., Wassmann, R., Neue, H., Lantin, R.S., Buendia, L.V., Ding, Y.P., & Wang, Z.Z. (2000). A four-year record of methane emissions from irrigated rice fields in the Beijing region of China. *Nutrient Cycling in Agroecosystems,* 58, 55-63.

Wassmann, R., Neue, H.U., Lantin, R.S., Buendia, L.V., & Renneberg, H. (2000). Characterization of methane emissions from rice fields in Asia. I. Comparison among fields sites in five countries. *Nutrient Cycling in Agroecosystems,* 58, 1-12.

Wesely, M.L., & Hicks, B.B. (2000). A review of the current status of knowledge on dry deposition. *Atmospheric Environment,* 34, 2261-2282.

XiuE, R., QinXue W., ChengLi, T., JinShui, W., KeLin, W., YongLi, Z., ZeJian, L., Masataka, W., & GuoYoung, T. (2007). Estimation of soil respiration in a paddy ecosystem in the subtropical region of China. *Chinese Science Bulletin,* 52, 2722-2730.

Yagi, K., Tsuruta, H., & Minami, K. (1997). Possible mitigation options from rice cultivation. *Nutrent Cycling in Agroecosystems,* 49, 213-220.

Yao, Z., Zheng, X., Xie, B., Liu, C., Mei, B., Dong, H., Butterbach-Bahl, K., & Zhu, J. (2009). Comparison of manual and automated chambers for field measurements of N_2O, $CH_{4,}$ CO_2 fluxes from cultivated land. *Atmospheric Environment,* 43(11), 1888-1896.

Zhu, R., Liu, Y., Sun, L., & Xu, H. (2007). Methane emissions from two Tundra wetlands in eastern Antarctica. *Atmospheric Environment,* 41, 4711-4722.

Zou, J., Huang, Y., & Jiang, J. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles,* 19, GB2021, 9.

*****

Chapter 2

Soil organic carbon sequestration in agriculture: Issues and priorities

A.K. Nayak[1*], Mohammad Shahid[1], A.K. Shukla[2], Anjani Kumar[1], R. Raja[1], Rahul Tripathi[1] and B.B. Panda[1]
[1]Central Rice Research Institute, Cuttack, Odisha, India
[2]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[*]e-mail: aknayak20@yahoo.com

Following the unprecedented expansion and intensification of agriculture in India, there is clear evidence of a decline in the organic carbon (OC) contents in many soils as a consequence; on the other hand it has been reported that good farming practices such as balanced fertilization and addition of crop residues either maintains or results in build up or depletion of soil organic carbon (SOC) stock (Swarup et al., 2000; Kong et al., 2005). The process of decline of organic matter is accelerated by the process of nutrient depletion, soil erosion and other forces of land degradation. In India, addition of organic matter was considered so important that numerous studies with organic manures were conducted in early saventies. The primary purpose was to determine their nutrient equivalence in comparison to chemical fertilizers. Despite the fact that organic manures contain almost all the essential plant nutrients and produce other non-nutrient benefits also, their value was principally assessed in terms of N only (Katyal, 1993; Tandon, 1997). The benefits of SOC are linked closely to the fact that it acts as a storehouse for nutrients, is a source of soil fertility, and contributes to soil aeration, thereby reducing soil compaction. Other benefits are related to the improvement of infiltration rates and increase in storage capacity for water. Furthermore, it acts as energy source for soil microorganisms. On the other hand intensive rice-based systems as reported from long-term experiments are showing symptoms of ‘fatigue’, witnessed by stagnating or declining yields (Dawe et al., 2000; Narang & Virmani 2001; Ladha et al., 2003). The depletion of soil fertility, associated with a reduction in quantity and/or quality of soil organic matter are some of the reasons attributed to this decline in yield (Ram 1998; Dawe et al., 2003).

Irrespective of its potential benefits to productivity and profitability, organic carbon might be sequestered by vegetation and soils, as a possible way of mitigating some detrimental effects of global climate change. Soils, managed agricultural soils in particular, represent a potentially significant low to no cost sink for greenhouse gases (GHGs) (Lal, 2004a; Pacala & Socolow, 2004). The great majority of agronomists and soil scientists agree that most agricultural soils can store more carbon and even a modest increase in carbon stocks across the large land areas used for agriculture would represent a significant mitigation of GHG emissions. Nevertheless, there are much uncertainty and debate on the total potential of soils to store additional carbon, the rate at which soils can store carbon, the permanence of this carbon sink, and best way to monitor changes in soil carbon stocks (Sanderman et al., 2010).

This chapter primarily discusses global organic carbon stocks with special reference to India, functions of organic carbon *vis-a-vis* agriculture, SOC sequestration and GHG mitigation potential, commoditization of SOC, stability and turnover of SOC, management options to make agricultural land to store additional SOC along with a summary of field evidence for stocks changes in India. This is followed by a discussion of some of the difficulties in accurately measuring change in SOC stocks.

Soil organic carbon

Soils contain large amounts of carbon in both organic and inorganic forms. Organic C is found in soils in the form of various organic compounds, collectively called soil organic matter (SOM). Soil organic matter includes all living and non-living organic material in all stages of decomposition. The turnover rate of SOM varies due to complex physical, chemical and biological interactions in soil. World soil estimated up to 1 meter depth comprises about 1550 Pg (Pg = Petagram = 1×10^{15} g = billion ton) as organic C is about 2 times the atmospheric pool of 780 Pg, and about 2.5 times the biotic pool of 620 Pg (Lal, 2009). The sheer size of the soil carbon pool and the annual flux of carbon passing through the soil are two of the reasons that SOC can play a significant role in mitigating GHG emissions. Historically, approximately 78 Pg C has been lost from the global soil pool due to land-use conversion for agriculture with approximately 26 Pg attributed to erosion and 52 Pg attributed to mineralization (Lal, 2004b). These large historic losses and the concomitant potential to return to pre-clearing SOC conditions are precisely the reason many researchers believe there is great potential for agricultural soils to sequester large amounts of atmospheric CO_2 relative to current SOC levels.

The Indian situation

Total SOC pool in soils of India is estimated at 21 Pg to 30 cm depth and 63 Pg to 150 cm depth. The SOC pool in soils of India is 2.2% of the world pool for 1 m depth and 2.6% to 2 m depth (Lal, 2004c). It is home to 1.1 billion or 16% of the world population and also supports 500 million domestic animals. The land resources comprises 329 m ha of geographical area with only 161.8 m ha of arable land (11.8% of the world) of which 57.0 m ha (21.3% of the world) is irrigated, 68.5 m ha of forest and woodland (1.6% of the world), 11.05 m ha of permanent pasture (0.3% of the world) and 7.95 m ha of permanent crops (6.0% of the world). Approximately 12 m ha of land is under one or more than one form of degradation arising due to water erosion, wind erosion, salinity, alkalinity, etc. The large land base has a potential to sequester C and enhance productivity while improving environment quality. Hence SOC sequestration, is a truly win-win situation.

Soil organic carbon productivity function and societal value

Soil organic matter plays an important role in many physical, chemical and biological processes in soil; its depletion has numerous adverse ecological and economic consequences. Increase in SOC is accompanied by increase in crop yield and productivity both under fertilized and unfertilized field. Soil organic carbon pool is an important component in formation of both micro- and macro-soil aggregates. The degree of aggregation and the stability of aggregates is directly proportional to SOC concentration. The role of SOC in the formation of stable soil aggregates has major implications for soil structure and, therefore, on water infiltration, water holding capacity, aeration, soil strength and resistance to root growth, and surface crusting (Scholes et al., 1994). In situations where soil moisture or soil strength are major limitations to plant growth, the greatest impact of SOC can be on these physical components of soil fertility. Because of high aggregation, soils with high SOC concentration have high available water holding capacity, low susceptibility to soil erosion, and have low losses of plant nutrients into the ground water. Use efficiency of fertilizer, irrigation and other input is high in soils with high SOC concentration. The most important function of SOC in soil is as a reserve of the nutrients required by plants, and ultimately by the human population. It has a less direct, but nonetheless important effect on nutrient supply through its influence on cation exchange capacity and on the capacity to adsorb anions; and these functions have additional important implications for the impact of toxic ions and biocidal agrochemicals (Woomer et al., 1994). All other factors remaining the same, soils with high SOC concentration have more agronomic/biomass productivity than those with low SOC concentration (Sandhu et al., 1996).

Soil organic carbon sequestration and greenhouse gas mitigation potential

A substantial portion of emitted carbon dioxide (CO_2) is sequestered in agricultural biomass and soil. The potential of agriculture (excluding bioenergy) to absorb large quantities of atmospheric CO_2 through soil carbon sequestration which has strong synergy with sustainable agriculture is widely being put forward as one of the mitigating options for climate change (Lal, 2002; Post et al., 2004). Thus, one of the more promising ways to reduce the rate of rise in atmospheric CO_2 is to encourage management policies that promote C sequestration in vegetation and ultimately in soils (Idso & Idso, 2002). Soils of India have lower SOC and hence there is a large sink capacity for atmospheric CO_2 sequestration. The IPCC 2nd assessment report estimated that the global potential CO_2 mitigation by agriculture could be in the range of 0.9–2.5 Gt C yr^{-1} (Gt = Giga tone = 1 x 10^9 t) including 0.5–1.6 Gt C yr^{-1} from biofuel production, 0.1 Gt C yr^{-1} from fuel savings and a limited restoration of previously cultivated wetland soils, the remaining 0.4–0.9 Gt C yr^{-1} mitigation potential from increased soil carbon sequestration. This does not mean that a sequestration potential of several hundreds of Tg C yr^{-1} would not be worth the trouble to realize, since such an improved soil humus management provides lots of other agricultural and environmental benefits and upset some of the GHG emissions from agriculture particularly rice.

It is estimated that globally, over the next century, agricultural soils could sequester 40 to 80 billion metric tons of carbon (Cole et al., 1997). Total potential of SOC sequestration in India is 12.7 to 16.5 Tg C yr^{-1} including 7 to 10 Tg C yr^{-1} for restoration of degraded soils and 6 to 7 Tg C yr^{-1} for adoption of recommended management practices (RMP) on agricultural soils (Lal, 2004c). The RMP related estimations are based on eco-region wise extrapolation and the rates of SOC sequestration from data of long-term experiments reported in the literature (Swarup, 1998). There could always be a possibility to have forward revision of these figures through adoption of varied innovative management practices and precision in estimation. The recent works on rate of carbon sequestration under different eco-regions in different cropping system with varied soil management options (Purukayastha et al., 2008; Kundu et al., 2007; Banger et al., 2009; Majumdar et al., 2008; Padre-Tirol et al., 2007; Nayak et al., 2009; Nayak et al., 2012) are some examples of technical potential of SOC sequestration. Similarly, different land degradation figure has been reported by various agencies due to use of different scale and methodologies, the first approximation of harmonized statistics shows that about 120.72 m ha as waste land and degraded land (Yadav & Sarkar, 2009), there is a need for its rehabilitation by different land use and soil management practices which could be an important sinks for carbon.

Soil carbon pools

Soil organic carbon can be partitioned into discrete pools according to its age or the amount of time it takes to turn over (Jenkinson & Raynor, 1977; Parton et al., 1987). Mean residence times of these pools are dependent on resistance to decay and the extent of protection against decomposition. The three main SOC pools are: (i) the active pool, with a turnover time in the order of weeks; (ii) the slow pool with a turnover time in the order of decades; and (iii) the passive pool with a turnover time in the order of millennia. The active pool is made up of readily oxidisable materials including, the microbial biomass carbon (MBC), light fractions of organic carbon (Soluble carbohydrates, extracellular enzyme, water extractable C), and is largely controlled by climate and residue inputs. About 10 to 30% active fraction is responsible for maintaining soil microorganisms.

The active soil C pool is most susceptible to soil management practices and is frequently used as an early indicator to SOM dynamics due to its faster turnover (Alvarez et al., 1998), so that changes caused by management or environmental stresses can be detected earlier in this pool than in the SOC pool as a whole. This can be particularly important in cases where environmental conditions change over a relatively short time. The slow and/ or very slow pools contain moderately decomposable material within macro- and micro aggregates and particulate organic carbon (POC) of 50 µm- 2.0 mm in size (Parton et al., 1987). The passive or recalcitrant pool includes humic acid, fulvic acid, humin, organo-mineral complex formed from the turnover of microbial and slow SOC that are chemically resistant to, or protected from further microbial degradation (Schimel et al., 1994). Humic substances have a complex aromatic structure. Many of the carbon components have hydrocarbon-type structures, whose C-C bonds and C-O-C linkages are difficult to break, and thus are not easily decomposed. Therefore, humic substances represent C component's resistance to biological decomposition in soils.

Stability and turnover of soil organic carbon

Three main mechanisms of SOC stabilization have been proposed: (1) chemical stabilization, (2) physical protection and (3) biochemical stabilization (Christensen, 1996; Stevenson, 1994). Largely chemical stabilization is the result of physico-chemical interaction of SOC with soil minerals through the process of cation bridging, ligand exchange and hydrogen bonding. It depends on various factors, including the characteristics of the organic matter, reactivity and specific surface of soil minerals, base-cation status, presence of Fe and Al oxides, pH, and redox conditions (Sollins et al., 1996; Baldock & Skjemstad, 2000; Von Lutzow et al., 2006). Physical protection of C is intimately tied to processes responsible for creation, turnover, and stabilization of soil aggregates at multiple, often hierarchical, scales (Tisdall & Oades, 1982; Jastrow & Miller, 1998; Six et al., 2004) which make the substrate spatially inaccessible to microbes and enzymes. However, its relevance is mainly limited to topsoil horizons. Biochemical stabilization is understood as the stabilization of SOC due to its own chemical composition (e.g. recalcitrant compounds such as lignin and polyphenols) and through chemical complexing processes (e.g. condensation reactions) in soil. There is an important class of biochemically recalcitrant compounds, generically termed black carbon, formed as result of fire (Lehmann et al., 2008) that can constitute a significant fraction of SOC in most soils.

Soil organic carbon cannot increase forever; it can only reach a certain balanced level (Hassink, 1996). The equilibrium point of SOC over a long time can be affected by many factors including climate, vegetation type, nutrient availability, disturbance, land use, and management practices (Six & Jastrow, 2002). Although tropical conditions favor SOC decline, its level seldom reaches a stage of complete exhaustion. Rather, SOC levels in cultivated soils tend to attain a steady state, described as a lower equilibrium limit (Buyanovsky & Wagner, 1998). There is also an upper limit for SOC that is the equilibrium content typical for a virgin ecosystem. If SOC loss by erosion is negligible, then SOC level in a properly managed soil fluctuates between these two extremes. Cultivation alone tends to stabilize the SOC at the lower equilibrium level, but SOC additions and fertilizer applications tend to shift the equilibrium towards the upper limit.

Hence, similar management practices may result in positive sequestration in one soil that is far from its maximum C stabilization level, while no change in another soil that is much closer to its upper equilibrium point. With the same input of organic material in terms of quantity and quality, clay soils contain more organic matter than sandy soils (Jenkinson, 1988). The annual change of SOC is equal to the annual mineralization amount minus the annual accumulation. Thus, a zero annual change of SOC can be interpreted as having reached a balance because total mineralization must be equal to total accumulation. Therefore, if the actual annual mineralization rate can be determined, it is possible to calculate the requirement of organic materials to reimburse the SOC lost by mineralization in the field, thereby maintaining SOC equilibrium (Chun-Yan et al., 2006). The mean residence times of SOM vary from less than one year to a few hundred years, if properly managed, the soil and plant have a significant potential to act as temporary carbon sinks. The human-induced carbon sinks, however, require a continuous effort, not only in order to be established, but also to be maintained.

Mechanism of soil organic carbon sequestration

Soil carbon sequestration refers to the storage of carbon in a stable form. It occurs through direct and indirect fixation of atmospheric CO_2. Direct soil carbon sequestration occurs by inorganic chemical reactions that convert CO_2 into soil inorganic carbon compounds such as calcium and magnesium carbonates. Direct plant carbon sequestration occurs as plants photosynthesize atmospheric CO_2 into plant biomass. Subsequently, some of this plant biomass is indirectly sequestered as SOC during decomposition processes of aboveground residues, belowground residues-accumulation of SOC due to the humification after plant death and rhizodeposition of root exudates and other root-borne organic substances released into the rhizosphere during plant growth as well as sloughing of root hairs and fine roots by root elongation. In total, various rhizodeposits accounting for up to 7 to 15% of net primary productivity (NPP) (Swinnen et al., 1995). Root exudates probably do not directly contribute much to soil C stocks as most of these low-molecular weight exudates have half-lives of only 20 to 40 minutes in soil (Boddy et al., 2007). In addition to this mycorrhizal fungi also contributes soil carbon stocks. Associations between plant roots and arbuscular mycorrhizal fungi (AMF) are ubiquitous in agroecosytems. Estimates of the amount of C allocated to fungal associates range from 4 to 20% of NPP (Graham, 2000) with a large fraction of this C supporting the growth of new hyphae which have been estimated to have a turnover rate of days to months, while the direct contributions to C stocks from hyphal turnover appears small (Zhu and Miller, 2003), the indirect effects that hyphal growth has on soil structure and aggregate stability can have significant impacts on total SOC stocks (Miller & Jastrow, 1990). However, a glyco protein like substances produced by hyphae termed as glomalin is having very slow decomposition. Photosyntetically active soil microflora also contribute some of the carbon inputs to the soil. The amount of carbon sequestered at a site reflects the long-term balance between carbon uptake and release mechanisms (Fig. 1). Many agronomic, forestry, and conservation practices, including suitable management practices, lead to a beneficial net gain in carbon fixation in soil.

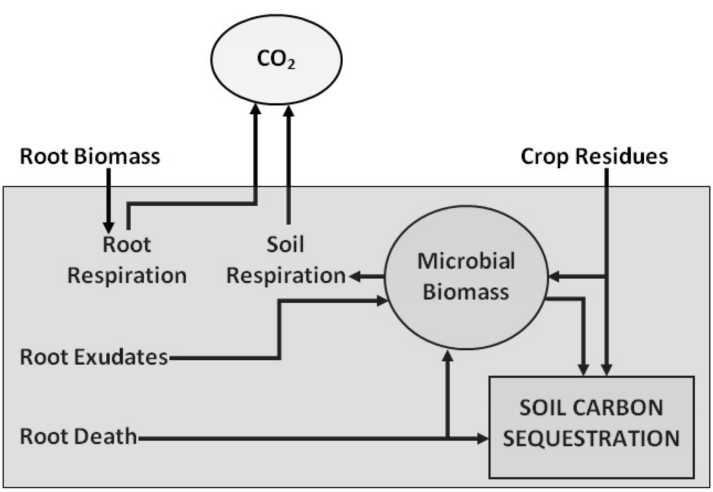


FIGURE 1. *Schematic diagram of soil carbon sequestration*

Commoditization of soil organic carbon

Soil organic matter is therefore one of our most important national resources; its unwise exploitation has been devastating; and it must be given its proper rank in any conservation policy. There is a need for determining a just value of soil organic carbon as commodity which can be traded like any other farm product. Under valuing a resource can lead to its abuse. It is important to identify criteria for determining the societal value of soil C for soil quality enhancement and ecosystem service, and using it for trading purposes. Carbon credits and its marketing are one such international attempt to mitigate the growth in concentrations of GHGs by commoditizing the carbon. Soil and biotic carbon is treated as a tradable commodity under clean development mechanism (CDM) of the Kyoto Protocol.

Clean development mechanism

Kyoto Protocol 1997 establishes the CDM, an institutional framework for direct foreign investments in GHG mitigation projects in developing countries. The objective of the CDM is to stimulate sustainable development in the developing countries, where the CDM projects will be implemented, the so-called host countries, and to give industrialized countries with high mitigation costs access to low-cost GHG offsets (formally Certified Emission Reductions, or CERs, in the Kyoto Protocol) in developing countries. With the CDM, the industrialized countries could count emission reductions and C-sink enhancement in developing countries against their commitments to reduce their GHG emissions. Recently political pressure to include soil activities under the Kyoto Protocol has been growing (New Scientist, 1998), even though the issue is a contentious one for the Parties to the UNFCCC (Nature, 2000). Article 3.3 of the Protocol explicitly mentions emissions from sources and removals by sinks as a direct consequence of human intervention affecting land-use changes, deforestation, reforestation and afforestation undertaken since 1990. Article 3.4 identifies agricultural land as a possible C source which should be included in the emission inventories that are prepared regularly by the UNFCCC Parties. However, the Protocol does not include provisions for national crediting for C sequestration in agricultural soils. During the first five-year commitment period (2008-2012) of the Kyoto Protocol, afforestation and reforestation projects will be eligible for crediting under the CDM. Other sink activities, such as forest conservation and soil C sequestration, will not be eligible. Still, soil C sequestration could become eligible for crediting under the CDM during subsequent commitment periods (Ringius, 2001).

Baseline, permanence and leakage

Baseline establishment is one of the key requirement i.e. carbon emission by sources or reduction by sinks in the absence of the CDM project. Baseline could be based on the most likely land use at the start of project. Additionality is defined as how much of the sequestration is a result of project implementation, beyond the estimated sequestration that would occur without the project. Permanence refers to the life span of the sequestered carbon; that is, whether the additional carbon sequestered at a site can be considered long-term or permanent with a low potential for later release or re-emission. It is evident that soil C re-accumulation schemes would need to be in place over long time-scales, raising the issue of whether C stocks are permanent or potentially reversible. How could stocks be protected against subsequent destructive interference resulting in losses? In this context, it should be realized that below-ground C normally is more protected than above-ground C during fire and other destructive events. Moreover, forests might be felled at a later point, but it is unlikely that agriculture will be reverted back to forests in India. Neither is it likely that farmers who benefit economically from conservation tillage will switch back to intensive tillage practices. More work is needed on the question of permanence of soil C sequestration. For instance, certain types of contracts may help to reduce the risk of reversal of C sequestration (Marland et al., 2001; Ellis, 2001). Carbon sequestration in soils might avoid problems of leakage because of its potential local benefits. The term leakage refers to the situation where a project unintentionally shifts an undesirable activity from the project site to another site, for instance a forest conservation project that prevents deforestation within the project area, and instead increases deforestation outside this area. However, soil C sequestration systems are less likely to create leakage effects because they will frequently be more desirable than alternative land-use systems.

Soil carbon trading

One carbon credit is equal to one ton of CO_2, or in some markets, CO_2 equivalent gases. Certified emission reductions (CERs) are a type of emissions unit (or carbon credits) issued by the CDM Executive board for emission reductions**.** Greenhouse gas accounting for soil carbon in agriculture under the Kyoto Protocol is based on the rate of change in carbon stock. Therefore, if conventional practice causes a decline and the new practice reduces the rate of loss, credit can be earned. This is a real reduction in emissions that could be counted under an emissions trading scheme.

Though, the Kyoto Protocol does not include provisions for national crediting for C sequestration in agricultural soils, many Nation States, MNCs invest in carbon sequestration efforts outside Kyoto. This meets Corporate Social Responsibility and also legislations as in California that requires carbon emission reductions or sink enhancement. This ensures the relaxed conditions of additionality, leakage, low transaction costs. It is estimated that conversion of all crop lands to conservation tillage in United States could sequester 25 Gt C over next 50 years. Some farmers have started receiving payments from coal burning utilities in emission trading arrangements brokered through Chicago Climate exchange (Baker et al., 2007) and payment are based on the premises that conservation tillage sequester the equivalent of 0.5 t CO_2 ha^{-1} yr^{-1}. Small and marginal farmers constitute major chunk of land holders in India. Aggregating small land holders (1-5 acre farm size) to make a meaningful transaction is a challenge for paying the benefit of carbon credits. However reputed organization can verify the activity undertaken for C sequestration or reducing C emission and award the VERs (verified emission reduction), which in turn can be traded. However there are many questions remained to be answered before soil carbon trading is reality in agriculture and these are:

a. Will agricultural soils be approved as means to meet GHG emissions commitments?

b. Will incentives be adequate so that landowners will maintain practices that sequester C?

c. Can incentives be designed so that countervailing C losses aren’t stimulated?

d. How will emissions reductions be integrated into total fabric of agricultural policy?

e. How will international agricultural activities come into play?

Management practices and soil carbon sequestration

The carbon storage below ground in the form of soil organic material may increase agricultural productivity and resilience to climate change. Many promising practices for soil carbon sequestration have been identified (Kimble et al., 2002). Long term studies have shown that improved fertilizer management, manuring and compost application, residue incorporation, crop rotation, green manuring, reduced tillage, adjusting irrigation method, restoration of waste land and agro-forestry enhance C storage. These practices not only promote sustainable agriculture but also mitigate the impact of climate change through both carbon sequestration and minimized emissions of GHGs. A single land use or management practice will not be effective at sequestering C in all regions (Lal et al., 1998). The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal et al., 2007). For example, a legume-based cropping system accumulates carbon at a lower rate than a cereal-based system, as its residues decompose more rapidly, and a soil under continuous flooded rice (rice-rice) accumulates carbon at a higher rate than under a rice-wheat rotation that is aerobic for part of the time. Long term experiments on rice based system has shown that balanced fertilization with NPK, however, caused an enrichment (9.3-51.8% over the control) of SOC, its extent being influenced by the cropping systems (Mandal et al., 2007). Similarly in long term rice-wheat experiment conducted in different agro-climatic zones of India, indicated that application of 50% NPK + 50% N through FYM in rice, 100% NPK in wheat (NPK + FYM), sequestered 0.39 0.50, 0.51 and 0.62 Mg C ha^{-1} yr^{-1} over control (no NPK fertilizers or organics), respectively at Ludhiana (Trans Gangetic Plains), Kanpur (Upper Gangetic Plains), Sabour (Middle Gangetic Plains) and Kalyani (Lower Gangetic Plains) (Nayak et al., 2012). In India each year 19.6 m t of straw of rice and wheat are burnt. If used as recycled biomass, this potentially translates into 3.85 m t of organic carbon, 59,000 tonnes of nitrogen, 2,000 tonnes of phosphorous and 34,000 tonnes of potassium and could be one of the potential options for improving the SOC stocks of soil. Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India, limiting the productivity of more than 2.5 m ha of otherwise arable lands in the Indo-Gangetic plains (Abrol & Bhumbla, 1971). Afforestation and reclamation of these lands through agroforestry systems have been reported to increase SOC content and improve the biological properties of sodic soils (Singh, 1996; Singh & Singh, 1997). When sodic soil was reclaimed and restored, we estimated SOC sequestration rate of 0.826 Mg C ha^{-1} yr^{-1} under *Prosopis juliflora* plantations and 0.689 Mg C ha^{-1} yr^{-1} under rice-wheat system (A.K. Nayak, personal communication 18 Feb, 2012). If offset payments to agricultural activities and payments to the carbon credit gained so in developing countries are allowed under a new climate change agreement, there is significant potential for mitigation activities involving land use including practices such as conservation agriculture, improved nutrient and water management and conversion of low-productivity crop land to pasture or agriculture and, in some cases, to forests.

Converting harvestable biomass to more recalcitrant C rather than completely combusting it offers a new approach to terrestrial sequestration as a potential side benefit of bioenergy production and is called Biochar or Biomass carbonization. With low-temperature pyrolysis, biomass is carbonized by heating under low-oxygen conditions while producing liquid and gaseous biofuels. Since combustion would not be complete, char-like substances would also be produced (Post et al., 2009). There is a scope for converting 19.6 million tonnes of straw of rice and wheat which are burnt annually in India into chemically stable forms – through biochar a clean process where heat and combustible gases are captured and used and C is stored in soil. Recent developments in genomics provide an unprecedented opportunity to identify genes, enzymes, biochemical pathways, and regulatory networks that underline rate-limiting steps in C acquisition, transport, and fate-and thereby yield new approaches to enhance terrestrial C sequestration. An investment in these new approaches to increase biomass production in agricultural crops and fast-growing trees in managed plantations is required to tap the potentials.

Measurement, monitoring and verification of soil organic carbon

To monitor carbon changes in soil and biotic pool, there is a need to improve the accuracy and costs of soil carbon sampling and measurement methodology. Stocks of organic C in soils are determined from two variables, namely SOC concentration and bulk density. Determination of organic carbon concentration is usually done by wet oxidation (Walkley & Black, 1934) or dry combustion (Wang & Anderson, 1998). The wet oxidation method is known to underestimate the amount of organic C in most samples so a correction factor needs to be applied. The magnitude of the correction factor is known to vary across soil types. Despite more accurate methods being available, the Walkley-Black technique is still used in some laboratories, particularly in India. Significant progress has been achieved during the past 10 years toward refining, enhancing, and adapting the method for measuring and monitoring soil carbon sequestration at field and regional scales. It is now possible to measure soil carbon changes as small as 1 Mg C ha^{-1} in a period of 3 years (McConkey et al., 2000) or estimate it with the use of simple or complex simulation models (Paustian et al., 1997; Smith, 2007). Measurement needs to be corrected and the measurement process needs to be unbiased, and more accurate measurements will be more broadly accepted. Article 3.4 of the Kyoto Protocol states that "uncertainties, transparency in reporting, and verifiability" should all be accounted for when monitoring carbon sink activities (Smith, 2004).

Recently several instruments have been developed for *in-situ* measurements of soil carbon which include laser-induced breakdown spectroscopy (Cremers et al., 2001), inelastic neutron scattering (Wielopolski, 2000), and diffuse reflectance IR spectroscopy (Christy et al., 2006) in the near-infrared and mid-infrared wavelength regions of 400–2500 and 2500–25,000 nm, respectively. Measurement and monitoring approaches using current or advanced methods need to be integrated to field-level and regional scales using computer simulation and remote sensing on some dynamic and geographically appropriate basis (Paustian et al., 1997; Smith, 2007). For trading purpose uncertainties in measurement, transparency in reporting, and verifiability should be accounted for when monitoring carbon sink activities.

Monitoring soil carbon changes at the project level are potentially costly and highly variable in carbon stocks on micro and macro scales due to multiple pools and small incremental changes anticipated. Hence estimation of soil carbon change could be undertaken by: 1) using SOC stock change values for specific practices reported in literature based on research studies; or 2) using process-based models of soil carbon dynamics, parameterised from experimental data; or 3) through a combination of baseline measurement to assess the vulnerability of soil carbon pools, and modeling informed by baseline measurements and understanding of the factors driving soil C dynamics.

Calculation of soil organic carbon stocks

Carbon results are generally reported in metric tons of CO_2 equivalents and compared to reference sample data to determine carbon additionality potential. Equations for conversion of carbon (C) results to CO_2 equivalents (Tian et al., 2009) are as follows:

Where %C = Mean percent organic carbon over the depth interval & treatment unit of interest

$$\text{SOC stock (Mg SOC ha}^{-1}\text{)} = \frac{\%\text{C}}{100} \times BD \times AD \times \frac{1000\ \text{m}^2}{\text{ha}}$$

BD = Mean bulk density (in Mg m^{-3})

AD = Soil depth interval of interest (in m)

Conversion to CO_2 equivalents in Mg (metric tons) per hectare:

Quantitative and reliable assessment methods of SOC are required to characterize soil properties and ecosystem functions. Soil organic C is a dynamic pool, and net changes in C sequestration often are more informative than absolute quantities. It is important to quantify temporal changes, whether caused by ecosystem development or by management practices, because they manifest changes in crucial properties of ecosystems (properties of soils) and of the ecosphere (atmospheric CO_2) (Ellert et al., 2002). Soil based approaches typically integrate various pieces of information, such as (i) temporal changes in SOC at single point, (ii) spatial variation in SOC distribution and associated cycling processes within landscape, (iii) geographical data on key variable such as land use, plant cover, soil properties, and climatic regime.

$$\frac{\text{Mg CO}_2}{\text{ha}} = \frac{44\ \text{g/mole CO}_2}{12\ \text{g/mole C}} \times \frac{\text{Mg C}}{\text{ha}}$$

Modelling of soil organic carbon stock changes

Over the years, several review studies on soil carbon dynamics have been carried out to establish the state-of-the-art, identify shortcomings in the current modeling approaches for estimating and projecting SOC changes. Jenkinson (1990) classified SOM models based on the number of pools as single homogenous, two and multi-component models. Paustian (1994) grouped multi-component models into organism-oriented and process-oriented, based on soil biology and biochemical processes. McGill (1996) grouped 10 process-oriented multi-component models based on relevant attributes, such as their static and dynamic nature, spatial and temporal scale, soil properties and homogeneity of soil horizons, and effect of microbial biomass on dynamics of organic matter. Smith et al. (1999) reviewed SOM models for tropical ecosystems, covering model use, input requirements, and outputs. Ma & Shaffer (2001) reviewed nine U.S. soil nitrogen dynamics models, as did McGechan & Wu (2001) for European models. They compared the descriptions of soil carbon and nitrogen dynamics in these models and the effect of various environmental factors on these processes. Grace & Merz (2001) classified models based on their main disciplinary orientation into ecological or agro-ecosystem models and agricultural or agronomic models, based on the data used for their calibration. RothC and Century (Cerri et al., 2004), have been demonstrated for several agricultural systems/ soil type combinations in India and abroad. Some of the SOM models and their characteristics for predicting SOC changes are given in Table 1.

TABLE 1. *Characteristics of various soil organic matter models for predicting soil organic carbon change*

Model	Land use system	Pool	Component
CANDY	Arable	3 OM pool (active, stable, inert)	C and N Sub model
CENTURY	Grass land, arable, forest	2 litter pool (AOM metabolic AOM structural) 3 SOM pool (active, passive, slow)	Forest sub-model, grass and crop sub-model, simulates the dynamics of C, N, P and S
DNDC	Arable	4 OM pool (litter, MBC, active humus, passive humus)	Soil physical environment, plant growth, organic matter decomposition, and denitrification
NCSOIL	Arable	2 residue pool , 4 SOM pool	NCSOIL is a stand-alone model
ROTHC	Soil in various system	Same as CENTURY	Does not contain a sub-model for plant production
SOMM	Forest	3 OM pool (litter, decompose dlitter, topsoil humus)	Stand-alone model
Verberne	Grass land	3 FOM pool (decomposable, structural, resistant), SOM Pool (nonprotected, protected, stabilised)	Soil water sub-model, soil organic matter sub-model, and soil N sub-model
Hybrid	Ecosystem	Same as CENTURY	Stand-alone model
ICBM	Arable	Two compartment model does not include plant processs	Stand-alone model

OM=Organic matter, SOM=Soil organic matter, AOM = Added organic matter, FOM =Fresh organic matter

Conclusions

Many of the management options discussed in the paper tend to increase overall sustainability of existing agricultural systems and as such are required to be adopted in respective agro-ecological situations in India. As a society, we will have to assess whether or not it is acceptable to compromise productivity of certain crops because they are not C neutral or net carbon storing. Overall, it is suggested that farming practices that increase soil C accumulation without compromising yield should be encouraged. However many mitigation options in the agricultural sector have numerous co-benefits in terms of food security, environmental sustainability and farm profitability, we believe that governmental policies that promote adoption of these best management practices should be pursued regardless of the final status of agricultural soils in any carbon pollution reduction scheme. Continued efforts should be made for evaluating different agrotechnologies having high sequestration potential and low global warming potential without compromising the yield. Due to the complex nature of agriculture in India, quantitative predictions of SOC sequestration rates will likely always entail a large degree of uncertainty. For proper accounting at regional and national scale, there is a need for robust modeling coupled with detailed measurements in representative systems combined with verification of management practices and yields via reporting and remote sensing with some economic discounting to factor in verification uncertainty. Developing mechanisms and procedures for carbon trade negotiations and formulation of protocols under CDM projects for making other sink activities in our country such as forest conservation and soil C sequestration eligible for carbon credit is needed so that the farmers and land managers can be benefited and this can futher be extended to cover degraded and desertified soils. The political and economic problems associated with implementing soil C sequestration programs and its trading worldwide needs to be studied.

References

Abrol, I.P., & Bhumbla, D.R. (1971). Saline and alkaline soils in India, their occurrence and management. *World Soil Resources, FAO Report*, 41, 42-51.

Alvarez, C.R., Alvarez, R., Grigera, M.S., & Lavado, R.S. (1998). Associations between organic matter fractions and the active soil microbial biomass. *Soil Biology and Biochemistry,* 30, 767-773.

Baker, J.M., Ochsner, T.E., Veterea, R.T., & Griffis, T.J. (2007). Tillage and soil carbon sequestration. What do we really know?. *Agriculture Ecosystems and Environment,* 118, 1-5.

Baldock, J.A., & Skjemstad, J.O. (2000). Role of the soil matrix and minerals in protecting natural organic materials against biological attack. *Organic Geochemistry,* 31, 697-710.

Banger, K., Kukal, S.S., Toor, G., Sudhir, K., & Hanumantharaju, T.H. (2009). Impact of long term additions of chemical fertilizers and farm yard manure on carbon and nitrogen sequestration under rice-cowpea cropping system in Semi-Arid Tropics. *Plant and Soil,* 318, 27-35.

Boddy, E., Hill, P.W., Farrar, J., & Jones, D.L. (2007). Fast turnover of low molecular weight components of the dissolved organic carbon pool of temperate grassland field soils. *Soil Biology & Biochemistry,* 39, 827-835.

Buyanovsky, G.A., & Wagner, G.H. (1998). Changing role of cultivated land in the global carbon cycle. *Biology and Fertility of Soils,* 27, 242-245.

Cerri, C.E.P., Paustian, K., Bernoux, M., Victoria, R.L., Melillo, J.M., & Cerri, C.C. (2004). Modeling changes in soil organic matter in Amazon forest to pasture conversion with the Century model. *Global Change Biology,* 10, 815-832.

Christensen, B.T. (1996). Carbon in primary and secondary organomineral complexes. In M.R. Carter, B.A. Stewart (Eds.), *Structure and organic matter storage in agricultural soils.* (pp. 97-165). Boca Raton, FL: CRC Press.

Christy, C.D., Drummond, P., & Lund, E. (2006). *Precision agriculture: Applications of an On the-Go Soil Reflectance Sensor*. Salina, Kans: Veris Technologies.

Chun-Yan, W.U., Chen, Y., Wang, J., & Wang, S. (2006). Estimation of turnover and equilibrium of soil organic matter using a mathematical approach. *Pedosphere*, 16(5), 634-645.

Cole, C.V., Duxbury, J., Freney, J., Heinemeyer, O., Minami, K., Mosier, A., Paustian, K., Rosenberg, N., Sampson, N., Sauerbeck, D., & Zhao, Q. (1997). Global estimates of potential mitigation of greenhouse gas emissions by agriculture. *Nutrient Cycling in Agroecosystems,* 49, 221-228.

Cremers, D.A., Ebinger, M.H., Breshears, D.D., Unkefer, P.J., Kammerdiener, S.A., Ferris, M.J., Catlett, K.M., & Brown, J.R. (2001). Measuring total soil carbon with laser-induced breakdown spectroscopy (LIBS). *Journal of Environmental Quality*, 30, 2202-2206.

Dawe, D., Dobermann, A., Ladha, J.K., Yadav, R.L., Bao, L., Gupta, R.K., Lal, P., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., & Zhen, Q.X. (2003). Do organic amendments improve yield trends and profitability in intensive rice systems?. *Field Crops Research,* 83, 191-213.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., & Zhen, Q.X. (2000). How widespread are yield declines in long-term rice experiments in Asia?. *Field Crops Research,* 66, 175-193.

Ellert, B.H., Janzen, H.H., & Entz, T. (2002). Assessment of a method to measure temporal change in soil carbon storage. *Soil Science Society of America Journal,* 66, 1687-1695.

Ellis, J. (2001). *Forestry projects: Permanence, credit accounting and lifetime*. Paris: OECD.

Grace, P.R., & Merz, S.K. (2001). Net Ecosystem Exchange workshop proceedings. CRC for Greenhouse Accounting, Canberra.

Graham, J.H. (2000). Assessing costs of *arbuscular* mycorrhizal symbiosis in agroecosystems. In G.K. Podila, D.D. Douds Jr. (Eds.), *Current advances in mycorrhizae research*. (pp. 127-139). St. Paul, MN: APS Press.

Hassink, J. (1996). Preservation of plant residues in soils differing in unsaturated protective capacity. *Soil Science Society of America Journal*, 60, 487-491.

Idso, S.B., & Idso, K.E. (2002). Global warming: Carbon sequestration to mitigate. In R. Lal (Ed.), *Encyclopedia of soil science*. (pp. 612-614). New York: Marcel Dekker.

Jastrow, J.D., & Miller, R.M. (1998). Soil aggregate stabilization and carbon sequestration: Feedbacks through organo-mineral associations. In R. Lal, J. M. Kimble, R. F. Follett, B.A. Stewart (Eds.), *Soil processes and the carbon cycle*. (pp. 207-273). Boca Raton, FL: CRC Press.

Jenkinson, D.S. (1990). The turnover of organic carbon and nitrogen in soil. *Philosophical Transactions of the Royal Society, London, B*329, 361-368.

Jenkinson, D.S. (1988). Soil organic matter and its dynamics. In A. Wild (Ed.), *Soil conditions and plant growth* (11th ed.). (pp. 564-607). UK: Longman Group.

Jenkinson, D.J., & Raynor, J.H. (1977). The turnover of soil organicmatter in some of the Rothamsted classical experiments. *Soil Science*, 123, 298-305.

Katyal, J.C. (1993). Integrated nutrient management and supply: An overview. *Proceedings of Indian National Science Academy*, B59(3&4), 161-172.

Kimble, J.M., Lal, R., & Follett, R.R. (2002). Agricultural practices and policy options for carbon sequestration: What we know and where we need to go?. In R. Lal, J.M. Kimble, & R.F. Follett (Eds.), *Agricultural practices and policies for carbon sequestration in soil*. (p. 512). New York: Lewis Publishers.

Kong, A.Y.Y., Six, J., Bryant, D.C., Denison, R.F., & van Kessel, C. (2005). The relationship between carbon input, aggregation, and soil organic carbon stabilization in sustainable cropping systems. *Soil Science Society of America Journal*, 69, 1078-1085.

Kundu, S., Bhattacharyya, R., Ved Prakash, Ghosh, B.N., & Gupta, H.S. (2007). Carbon sequestration and relationship between carbon addition and storage under rainfed soybean–wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research,* 92, 87-95.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal,, H.P., Gupta, R.K., & Hobbs, P.R. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research,* 81, 159-180.

Lal, R. (2002). Carbon sequestration in drylands. *Annals of Arid Lands,* 38, 1-11.

Lal, R. (2004a). Soil carbon sequestration impacts on global climate change and food security. *Science,* 304, 1623-1627.

Lal, R. (2004b). Soil carbon sequestration to mitigate climate change. *Geoderma,* 123, 1-22.

Lal, R. (2004c). Soil carbon sequestration in India. *Climatic Change,* 65, 277-296.

Lal, R., Kimble, J.M., Follett, R.F., & Cole, C.V. (1998). *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*. Chelsea, Mich.: Ann Arbor Press.

Lal, R. (2009). Soil carbon sequestration for climate change mitigation and food security. *Platinum jubilee of ISSS Souvenir*. (pp. 39-46). New Delhi: Indian Society of Soil Science.

Lehmann, J., Skjemstad, J., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P., & Krull, E. (2008). Australian climate-carbon cycle feedback reduced by soil black carbon. *Nature Geoscience,* 1, 832-835.

Ma, L., & Shaffer, M.J. (2001). A review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. In M.J. Shaffer, L. Ma, S. Hansen (Eds.), *Modeling carbon and nitrogen dynamics for soil management*. (pp. 55-102). Boca Raton, FL: Lewis Publishers.

Majumdar, B., Mandal, B., Bandopadhyay, P.K., Gangopadhyay, A., Mani, P.K., Kundu, A.L., & Majumdar, D. (2008). Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal,* 72, 775-785.

Mandal, B., Majumder, B., Bandopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaroy, R.N., Misra, A.K., Chowdhuri, J., Saha, M.N., & Kundu, S. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology,* 13, 357-369.

Marland, G., Fruit, K., & Sedjo, R. (2001). Accounting for sequestered carbon: The question of permanence. *Environmental Science and Policy,* 4, 259-268.

McConkey, B.G., Liang, L.Y., Padbury, G., & Heck, R. (2000). Prairie soil carbon balance project: Carbon sequestration from adoption of conservation cropping practices. *Final Report to GEMCo.*190, Saskatoon, Sask.

McGechan, M.B., & Wu, L. (2001). A review of carbon and nitrogen processes in European soil nitrogen dynamics models. In M.J. Shaffer, L. Ma, S. Hansen (Eds.), *Modeling carbon and nitrogen dynamics for soil management*. (pp. 103-171). Boca Raton FL: Lewis Publishers.

McGill, W. (1996). Review and classification of ten soil organic matter (SOM) models. In D.S. Powlson, P. Smith, J.U. Smith (Eds.), *Evaluation of soil organic matter models using existing long-term datasets*. (pp. 111-132). Proceedings of the NATO Advanced Research workshop, NATO ASI Series I, Vol. 38. Berlin: Springer Verlag.

Miller, R.M., & Jastrow, J.D. (1990). Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. *Soil Biology & Biochemistry,* 22, 579-584.

Narang, R.S., & Virmani, S.M. (2001). Rice-wheat cropping systems of the Indo-Gangetic Plains of India. In *Rice-Wheat Consortium for the Indo-Gangetic Plains, New Delhi, and International Crops Research Institute for the Semi-Arid Tropics*, Patancheru, Andhra Pradesh, India, pp. 36.

Nature, 30 November 2000. *Critical politics of carbon sinks*. 408(6812), 501.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, Sonali. P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research,* 127, 129-139.

Nayak, P., Patel, D., Ramakrishnan, B., Mishra, A.K., & Samantaray, R.N. (2009). Long-term application effects of chemical fertilizer and compost on soil carbon under intensive rice–rice cultivation. *Nutrient Cycling in Agroecosystem,* 83, 259-269.

New Scientist, 21 November 1998. *Down to Earth*. 160(2161), 17.

Pacala, S., & Socolow, R. (2004). Stabilization wedges: Solving the climate problem for the next 50 years with current technologies. *Science,* 305, 968-972.

Padre-Tirol, A., Ladha, J.K., Regmi, A.P., Bhandari, A.L., & Inubushi, K. (2007). Organic amendments affect soil parameters in two long term rice-wheat experiments. *Soil Science Society of America Journal,* 71, 442-452.

Parton, W.J., Schimel, D.S., Cole, C.V., & Ojima, D.S. (1987). Analysis of factors controlling soil organic matter levels in great plains grasslands. *Soil Science Society of America Journal,* 51, 1173–1179.

Paustian, K. (1994). Modelling soil biology and biochemical processes for sustainable agriculture research. In C.E. Pankhurst, D.M. Doube, V.V.S.R. Gupta, P.R. Grace (Eds.), *Soil Biota: Management in sustainable farming systems*. (pp. 182-193). Canberra: CSIRO.

Paustian, K., Andren, O., Janzen, H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., & Woomer, P. (1997). Agricultural soils as a C sink to offset CO_2 emissions. *Soil Use and Management,* 13, 230-244.

Post, W.M., Izarurralde, R.C., Jastrow, J.D., McCarl, B.A., Amonette, J.E., Bailey, V.L., Jardien, P.M., West, T.O., & Zhou, J. (2004). Enhancement of carbon sequestration in U.S. Soils. *BioScience*, 54, 895-908.

Post Wilfred, M., Amonette, J.E., Birdsey, R.G., Charles, T., Izaurralde, R.C., Jardine, P.M., Jastrow, J., Lal, R., Marland, G., McCarl, B.A., Thomson, A.M., West, T.O., Wullschleger, S.D., & Metting, F.B. (2009). Terrestrial biological carbon sequestration: Science for enhancement and implementation. In *Carbon sequestration and its role in the global carbon cycle.* (pp. 73-88). Geophysical Monograph Series, 183.

Purukayastha, T.J., Rudrappa, L., Singh, D., Swarup, A., & Bhadraray, S. (2008). Long-term impact of fertilizers on soil organic carbon pools in maize-wheat-cowpea cropping system. *Geoderma,* 144, 370-378.

Ram, N. (1998). Effect of continuous fertilizer use on soil fertility and productivity of a *Mollisol*. In A. Swarup, R.D. Damodar & R.N. Prasad (Eds.), *Long-term soil fertility management through integrated nutrient supply*. (pp. 229-237). Bhopal, India: Indian Institute of Soil Science.

Ringius, L. (2001). What prospects for soil carbon sequestration in the CDM? COP-6 and beyond. *Energy & Environment,* 12, 275-285.

Sanderman, J., Farquharson, R., & Baldock, J. (2010). Soil carbon sequestration potential: A review for Australian agriculture. A report prepared for Department of Climate Change and Energy Efficiency, pp. 89.

Sandhu, K.S., Benbi, D.K., & Prihar, S.S. (1996). Dryland wheat yields in relation to soil organic carbon, applied nitrogen, stored water and rainfall distribution. *Fertilizer Research,* 44, 9-15.

Scholes, R.J., Dalal, R., & Singer, S. (1994). Soil physics and fertility: The effects of water, temperature and texture. In P.L. Woomer, M.J. Swift (Eds.), *The biological management of soil fertility*. (pp. 117-136). Chichester: John Wiley and Sons.

Schimel, D.S., Braswell, B.H., Holland, E.A., McKeown, R., Ojima, D.S., Painter, T.H., Parton, W.J., & Townsend, A.R. (1994). Climatic, edaphic and biotic controls over storage and turnover of carbon in soils. *Global Biogeochemical Cycles,* 8, 279-293.

Singh, B. (1996). Influence of forest litter on reclamation of semiarid sodic soils. *Arid Soil Research and Rehabilitation,* 10, 201-211.

Singh, G., & Singh, N.T. (1997). Effect of land use practices on organic carbon dynamics of sodic soils. In R. Lal, J. Kimble, R. Follett (Eds.), *Soil properties and their management for carbon sequestration*. (pp. 89-105). USDA-Natural Resources Conservation Service, National Soil Survey Centre.

Six, J., & Jastrow, J.D. (2002). Organic matter turnover. In R. Lal (Ed.), *Encyclopedia of soil science*. (pp. 936-942). New York: Marcel Dekker Inc.

Six, J., Bossuyt, H., Degryze, S., & Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research,* 79, 7-31.

Smith, G.A. (2007). Harnessing farms and forests in the low carbon economy: How to create, measure, and verify greenhouse gas offsets. In Z. Willey, W. Chameides (Eds.), *Harnessing farms and forests in the low carbon economy: How to create, measure, and verify greenhouse gas offsets*? (pp. 220). Durham, NC: Duke University Press.

Smith, P. (2004). Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol. *Soil Use and Management*, 20, 264-270.

Smith, P., Falloon, P., Coleman, K., Smith, J.U., Piccolo, M., Cerri, C.C., Bernoux, M., Jenkinson, D.S., Ingram, J.S.I., Szabó, J., & Pásztor, L. (1999). Modelling soil carbon dynamics in tropical ecosystems. In R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (Eds.), *Global climate change and tropical soils*: *Advances in soil science.* (pp. 341-364). Boca Raton, FL: CRC Press Inc.

Sollins, P., Hofmann, P., & Caldwell, B.A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma,* 74, 65-105.

Stevenson, F.J. (1994). *Humus chemistry: Genesis, composition, reactions*. New York: John Wiley & Sons.

Swarup, A. (1998). Emerging soil fertility management issues for sustainable crop productivity in irrigated systems. In A. Swarup, D.D. Reddy, R.N. Prasad (Eds.), *Long term soil fertility management through Integrated Plant Nutrient Supply.* (pp. 54-68). Bhopal, India: IISS.

Swarup, A., Manna, M.C., & Singh, G.B. (2000). Impact of land use and management practices on organic carbon dynamics in soils of India. In R. Lal, J.M. Kimble, B.A. Stewart (Eds.), *Global climate change and tropical ecosystems*. (pp. 261-281). Boca Raton, FL: CRC/Lewis Publishers.

Swinnen, J., Vanveen, J.A., & Merckx, R. (1995). Carbon fluxes in the rhizosphere of winter wheat and spring barley with conventional *vs* integrated farming. *Soil Biology & Biochemistry,* 27, 811-820.

Tandon, H.L.S. (1997). Organic residues: An assessment of potential supplies, their contribution to agricultural productivity and policy issues for Indian agriculture from 2000 to 2025. In I.S. Kanwar, J.C. Katyal (Eds.), *Plant nutrient needs, supply, efficiency and policy issues* (*2000-2025*). New Delhi, India: National Academy of Agricultural Sciences.

Tian, G., Granato, T.C., Cox, A.E., Pietz, R.I., Carlson, C.R. Jr., & Abedin, Z. (2009). Soil carbon sequestration resulting from long-term application of biosolids for land reclamation. *Journal of Environmental Quality*, 37, 1-14.

Tisdall, J.M., & Oades, J.M. (1982). Organic matter and water-stable aggregates in soils. *Journal of Soil Science,* 33, 141-163.

Von Lutzow, M., Kogel-Knabner, I., Ekschmitt, K., Matzner, E., Guggenberger, G., Marschner, B., & Flessa, H. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions - A review. *European Journal of Soil Science,* 57, 426-445.

Walkley, A., & Black, I.A. (1934). An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil Science,* 37, 29-38.

Wang, D.L., & Anderson, D.W. (1998). Direct measurement of organic carbon content in soils by the Leco CR-12 Carbon Analyzer. *Communications in Soil Science and Plant Analysis,* 29, 15-21.

Wielopolski, L., Orion, I., Hendrey, G., & Roger, H. (2000). Soil carbon measurements using inelastic neutron scattering. *IEEE Trans. Nuclear Science,* 47, 914-917.

Woomer, P.L., Martin A., Albrecht A., Resch D.V.S., & Scharpenseel, H.W. (1994). The importance and management of soil organic matter in the Tropics. In P.L. Woomer, M.J. Swift (Eds.), *The biological management of soil fertility*. (pp. 47-80). Chichester: John Wiley and Sons.

Yadav, J.S.P., & Sarkar, D. (2009). Soil degradation with special reference to India. In *Platinum jubilee of ISSS Souvenir.* (pp.15-21). New Delhi: Indian Society of Soil Science.

Zhu, Y.G., & Miller, R.M. (2003). Carbon cycling by *arbuscular* mycorrhizal fungi in soil-plant systems. *Trends in Plant Science,* 8, 407-409.

*****

Chapter 3

Gaseous carbon emissions from rice and rice based cropping systems

P. Bhattacharyya[1*], K.S. Roy[1], S. Neogi[1], Sangita Mohanty[1], T.K. Adhya[1] and D. Srinivas[2]
[1]Central Rice Research Institute, Cuttack, Odisha, India
[2]APRRI and RARS, Maruteru, Andhra Pradesh, India
* e-mail: pratap162001@yahoo.co.in

Rice paddies play an important role in the global budget of greenhouse gases (GHGs) *viz.* carbon dioxide (CO_2) and methane (CH_4), contributing to gaseous-C emissions to atmosphere (IPCC, 2007). Rice is flooded most of the times during its cultivation period. That's why many of the factors controlling gas exchange between rice paddies and atmosphere are unique and vary from other dryland agricultural practices. Net exchanges of gaseous-C (CO_2-C + CH_4-C) between rice paddies and atmosphere are regulated by various physico-biochemical processes. Methane and CO_2 budget in rice fields are both affected by structure and dynamics of anaerobic and/ or aerobic conditions in the soil, but specific impacts are often diverging for both gases.

Among the different GHGs, CO_2 is the largest contributor to the anthropogenic greenhouse effect, accounting 29×10^{12} t CO_2 yr^{-1}, representing approximately 4% of global C fluxes involving the atmosphere. Industrial activity is the major source of atmospheric CO_2 including minor contribution from agriculture in the form of biomass burning associated with land-use change. On the contrary, CH_4 with an annual global budget of 5×10^9 t CH_4 yr^{-1} and N_2O with an annual global budget of 3×10^9 t N_2O yr^{-1}, exert major influence on the global climate. In order to assess the total impact of the different GHGs, it is important to remember that each gas has a biological component and soils contribute to the budgets of many atmospheric trace gases by acting as either sources or sinks. The CO_2 release into the atmosphere is both chemically and biologically mediated processes. Conversely, both CH_4 production and its consumption are biologically mediated.

Rice, the most important cereal crop in India, is preferentially grown under submerged conditions due to better yields than in upland soil and positive response to modern agricultural practices. The dynamics of C and N in the submerged rice soil is different from that of aerobic soils because submerged rice soils are maintained at lower redox potentials. Predominantly anaerobic flooded soils promote the production of CH_4, a major end product of anaerobic decomposition of organic matter (native or added). Intermittent flooding and drainage, while retarding CH_4 emission promote the emission of CO_2, another important GHG from soils, especially when heavily fertilized with N fertilizers.

The existence of anaerobic soil due to overlying floodwater and the change in micrometeorological environment upon flooding influence photosynthesis, respiration as well as root activity of rice plants. Algae present in the floodwater may also affect CO_2 exchange between rice paddies and the atmosphere. During the daytime plant photosynthesis leads to uptake of CO_2 from the atmosphere while respiration at night leads to an efflux of CO_2 to the atmosphere. Net fluxes of soil-borne CO_2 in rice fields are associated with changes in agricultural management, e.g., tillage, irrigation pattern, etc. However, most rice production systems indirectly entail emission of CO_2 from fossil fuel consumption due to farm operation and fertilizer production.

Although the CO_2 budget is almost in balance, CO_2 fluxes between agricultural lands and the atmosphere are large in both directions (120 Pg C yr^{-1}) (Denman et al., 2007). Part of the CO_2 efflux derives from decomposition of soil organic matter. Carbon storage in soils has been estimated to be 1500 Pg C, which is double that in the atmosphere (730 Pg C) (Prentice et al., 2001). Thus, to sustain soil carbon storage, it is important to reduce CO_2 emission from agricultural soils.

On the other hand paddy fields are one of the largest sources in the global budget of CH_4. The estimate of global CH_4 emissions from rice paddies is around 60 Tg $year^{-1}$, but with uncertainty ranging from 20 to 100 Tg $year^{-1}$ (IPCC, 1995). Actually CH_4 is released to the atmosphere by ebullition, diffusion across floodwater-air interface and by transport through aerenchyma. In undisturbed paddy fields upto 90% of CH_4 emission occurs through aerenchyma (Minami & Neue, 1994). Flooded soils planted to rice are conducive to the production and emission of CH_4 due to the presence of methanogenic bacteria that utilize readily decomposable organic compounds under anaerobic soil condition. Both CH_4 production and emission from flooded rice soils are strongly influenced by several soil processes including changes in soil redox status and pH, dynamics of substrate and nutrient availability and textural stratification (Bouwman, 1990). In addition, common cultivation practices such as application of agrochemicals also affect CH_4 efflux from flooded rice soils (Neue et al., 1997). While organic matter amendment generally increases CH_4 emission (Neue et al., 1997), CH_4 efflux is also strongly influenced by the type, method and rate of application of chemical fertilizer. With the intensification of rice cultivation to meet the needs for rising population, CH_4 emission from flooded rice paddy ecosystem is likely to increase.

A range of soil, climatic variables and agricultural management practices influence the production and emission of gaseous carbon from the rice and rice-based production systems. Among these soil temperature, soil moisture, pH, soil organic matter, organic manure and fertilizer application, rainfall, humidity, air temperature, solar radiation, high microbial activity and biomass turnover rate, water management, cultivar or variety, tillage practice, etc. are important factors. As there is considerable uncertainty regarding the magnitude of net fluxes of gaseous-C emissions from rice paddies, field studies to monitor and measure net fluxes and to understand the controlling factors behind this should be properly designed for quantification and budgeting of net carbon fluxes from rice-based production systems during cultivation and fallow periods.

Net ecosystem exchange

The most important processes affecting carbon balance of a terrestrial ecosystem are photosynthesis of above-ground vegetation and soil respiration. The net ecosystem exchange (NEE) of CO_2 between the biosphere and the atmosphere is the balance between fluxes associated with photosynthetic assimilation by the foliage (Gross ecosystem production, GEP) and respiratory effluxes from autotrophs (roots) and heterotrophs (microbial and soil fauna).The relationship between production and decomposition determines whether a system is a sink or a source of atmospheric CO_2. An accurate assessment of soil and plant respiration is crucial for understanding and predicting ecosystem responses to anthropogenic perturbations *viz.* climate change, pollution and agriculture. However, the seasonal variation in ecosystem CO_2 exchange with the atmosphere occurs in response to meteorological conditions and physiological activities of rice crop.

Soil respiration is the major pathway of C efflux from terrestrial systems and represents an integrated reporter of ecosystem functioning (Mills et al., 2011). Understanding controls on soil respiration is critical because relatively small changes in respiration rates may radically alter atmospheric concentrations of CO_2 and also soil C sequestration. Reducing CO_2 emissions from soils may help to increase sequestration of atmospheric CO_2 in soil. Soil respiration includes root and microbial respiration, and bulk turnover of organic matter (OM) which all contributes to the release of CO_2 (Hill et al., 2004). Accurate quantification of gaseous CO_2-C fluxes from soil remains the main factor for furthering the understanding of soil C flow and ecosystem resilience (Davidson et al., 2002). Soil respiration seems to be one of the primary fluxes of C between soils and the atmosphere, with a global release of 75 Pg C $year^{-1}$. Soil and plant respiration is generally measured by the soil and or canopy chamber, enclosing the soil and or canopy for specified time and then measuring the liberated CO_2 due to respiration with the help of infrared gas analyzer.

Soil CO_2 emission integrates all the components of soil CO_2 production, rhizospheric respiration as well as soil microbial respiration in rice and rice-based cropping systems. Variations in soil respiration i.e., soil CO_2 fluxes are influenced by agronomic management practices (*viz.* organic or inorganic fertilization). Agricultural operations affect soil CO_2 flux by changing the soil environment like soil pH, soil temperature, soil moisture, soil aeration, C/N ratio of substances, etc. These may have significant impact on soil microbial activities and the decomposition processes instrumental for transforming plant-derived C to soil organic matter and CO_2. The applications of chemical fertilizers alone or in combination with organic manures, soil and water management in rice paddies are crucial for predicting future trend of CO_2 emissions from rice paddy ecologies and for taking steps to mitigate climate changes due to agricultural practices.

Net ecosystem carbon dioxide exchange in rice field

In China, eddy covariance (EC) technique-based estimations revealed that the soil respiration rates at night times during the fallow periods were 52-398 mg m^{-2} h^{-1}. Annual average soil respiration rates and total soil respiration of paddy soil in the subtropical region of China were estimated to be 178.5-259.9 mg m^{-2} h^{-1} and 1.56-2.28 kg m^{-2} yr^{-1}, respectively (XiuE et al., 2007).

Diurnal variation of CO_2 fluxes during rice maturity period was noticed in Taiwan by eddy covariance measurements (Tseng et al., 2010). Fluxes of CO_2 were always positive during night hours, whereas during the daytime the flux was found to be negative. Thus the rice paddy ecosystem behaved as a CO_2 source during night hours and a CO_2 sink during the day. As a matter of fact the rice paddy ecosystem behaved as a potential CO_2 source with a daily average flux of 0.71 µmol CO_2 m^{-2} s^{-1}.

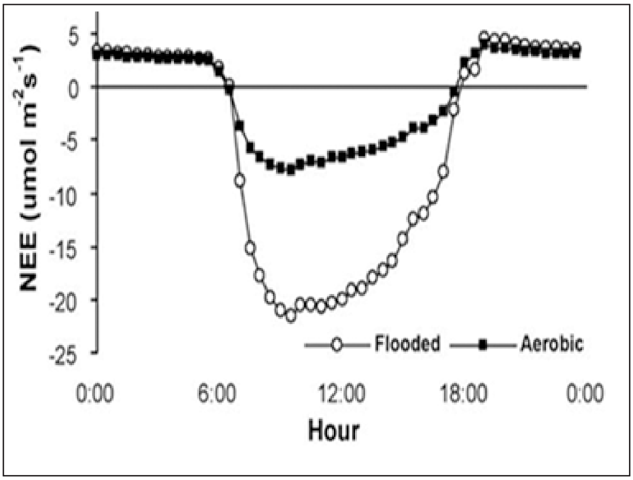


FIGURE 1. *Diurnal variation of net ecosystem cabon dioxide exchange of aerobic and flooded rice field at heading stage at IRRI, Philippines*

At IRRI, Philippines, NEE was found to be negative during the daytime and positive during the night time for both flooded and aerobic rice fields. From active tillering to panicle initiation stage NEE was about -10 µmol CO_2 m^{-2} s^{-1} and it reached as low as -22 µmol CO_2 m^{-2} s^{-1} during heading to flowering stage in flooded rice fields. From tillering to ripening stage, the flooded rice fields behaved as net CO_2 sink on a daily basis and maximum uptake was noticed during heading to flowering stage with a average value of -5.98 g C m^{-2} d^{-1}. Aerobic rice fields became net sink for CO_2 at reproductive stage and continued to behave as net CO_2 sink at harvest stage also with the mean value of -2.31 g C m^{-2} d^{-1}. The total C budget integrated over the cropping period showed that in flooded rice fields NEE was about three times higher than that of aerobic rice fields NEE. The gross primary production (GPP) and ecosystem respiration (RE) values for flooded rice fields were 778 and 521 g C m^{-2} and in case of aerobic rice fields the values of GPP and RE were 515 and 430 g C m^{-2}, respectively (Alberto et al., 2009).

Methane emissions from rice fields

Rice fields are considered to be an important anthropogenic source for CH_4 and contribute up to 20% or ~100 Tg CH_4 to the global budget on an annual basis (Houghton et al., 1996). With intensification of rice cultivation during the coming decades, CH_4 emission from this economically important but ecologically fragile ecosystem is anticipated to increase. Despite recent studies on identification of controlling variables (Neue et al., 1997), the uncertainty in the global CH_4 sources estimated for rice paddies are still very high (Houghton et al., 1996) due to large spatial differences. Such uncertainty in the sources estimated largely from different soil types as well as variations between crop management in space and time. Refinement in methodologies and more measurements incorporating site-specific practices are essential for an accurate assessment of the contribution of paddy ecosystem to global CH_4 budget. India produces annually 92.83 m t of rice on an area of 43.77 m ha (DOES, 2011). The rice growing areas of India can be broadly categorized into rainfed upland, rainfed lowland and irrigated medium land, representing about 15, 40 and 45% of total rice area of the country. In India, 48% of the country's rice area is irrigated while the rest is under rainfed situations. Flooded rice fields are the potent sources of CH_4 (Houghton et al., 1996) as well as can also act as sink for CH_4. The source and sink capacity entirely depends on field management practices. Methane predominantly escapes to the atmosphere through the aerenchyma of the rice plant (Fig. 2). The documented morphology of the aerenchyma allows the reconstruction of the vertical gas transfer including the speed-limiting passage from root to culm. Nutrient supply affects development of aerenchyma as well as root exudation and thus the budget of CH_4. Methane emission in rice fields is affected by the properties, structure and dynamics of the submerged soil. Its emission increases under continuous flooding in rice fields and it escapes to the atmosphere through the aerenchyma of the rice plant.

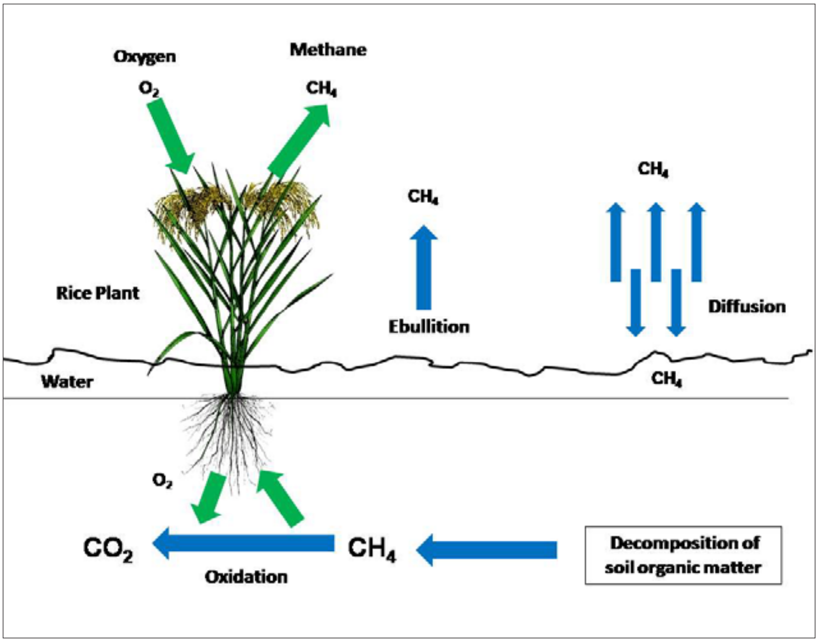


FIGURE 2. *Methane emission from flooded rice field*

Rice ecosystems and methane emission

Cultivated rice, the major crop in tropical system is grown under flooded condition. In many rice-growing areas, wetlands may have at least one wet growing season, but may be dry, moist, or without water in other seasons. The accumulation and depletion of Fe and Mn, the redoximorphic features indicate the “aquic” soil conditions. A typical soil profile of a flooded rice soil has many horizons. The horizon, “ Ofw” is well described as the layer of standing water that becomes the habitat of bacteria, phytoplankton, macrophytes, zooplankton, and aquatic invertebrates and vertebrates. The “Apox” horizon is the floodwater-soil interface while the “Apg” horizon is the reduced puddled layer. The “Apx” layer has increased bulk density, high mechanical strength and low permeability. The ‘B” horizon depends highly on the water regime. Upon submergence, soils undergo characteristic physical, chemical and biological changes. Variations in the edaphic factors and hydrological conditions contribute more to the diverse nature of rice growing conditions.

Irrigated rice has by far the highest CH_4 source strength about 70-80% of all rice ecologies. It accounts for 97% of the CH_4 emission from rice fields in East Asia and for 60% of the CH_4 emitted from South and Southeast Asian rice fields, respectively. (Wassmann et al., 2000b). Rainfed rice ecologies contribute about 15% of CH_4 from the global rice area (Wassmann et al., 2000b). Wassmann et al. (2000a) reported that deepwater rice ecologies contribute about 10% of the global CH_4 from the rice source. The differences in crop calendars, season lengths, cultural practices, diverse cultivars and many other factors impede direct comparisons of CH_4 emissions from different rice ecologies. Though the irrigated rice is the largest source of CH_4, it also the most promising target for mitigating CH_4 emissions (Wassmann & Aulakh, 2000).

Mechanism of methane formation and transformation

The emission of CH_4 to environments from the field, whether terrestrial or aquatic, depend on a multitude of factors including the biological processes by which CH_{4-} is produced and consumed. The net emission from an agricultural system is the result of production (methanogenesis) and consumption (methanotrophy) and whether the net emission will be positive or negative, depends on the relative magnitudes of these processes. Though *Methanosarcina* and *Methanosaeta* are the smaller number in the ratio of methanogenic population, they account for two-thirds of CH_4 produced. However, the reaction provides little energy and the net result is low growth rate of acetotrophic methanogens. Using CH_3F, it has been clearly shown that about 70-77 % of the methanogenic population is H_2 and CO_2 utilizing methanogens and contributes only 25-30% of the CH_{4-} production. However, CH_{4-} production in rice fields depends on soil characteristics (organic carbon), rice varieties (especially root volume and exudation), cultural practices (fertilizer application, water management, pre-cultural practices) and methylotrophy. It has been known that SO_4 and minerals like Mo, Fe, Mn and Ni play an important role in the methanogenic environments (Table 1).

TABLE 1. *Sequence of reduction reactions in submerged soil*

Element		After reduction	Redox potential (Eh)
O_2	→	H_2O	
NO_3^-	→	N_2O	< 0.2 V
Mn^{+4}	→	Mn^{+2}	0.2 to 0.4 V
Fe^{+3}	→	Fe^{+2}	0.0 to -0.15 V
SO_4^{-2}	→	S^{-2}	< -0.15 V
CO_2	→	CH_4	< -0.2 V
H^+	→	H_2	

Methanogenesis

Soils are the most important source in the atmospheric CH_4 budget, contributing about 60%. The active CH_4 emitting soils usually include all kinds of wetlands including flooded rice fields. In wetland soils, anoxic conditions establish in most of the soil because O_2 diffusion from the atmosphere is limiting. Mineralization of organic matter in such soils favoring the activities of fermenting and methanogenic bacteria produces CH_4 and CO_2 (Eq. 1).

$$C_6H_{12}O_6 \longrightarrow 3\,CO_2 + 3\,CH_4 \quad \text{..........} \quad (1)$$

The conversion of complex organic matter to CH_4 requires a microbial food web (consortium) composed of several interacting metabolic groups of anaerobic (facultative and strict) microorganisms:

(a) Hydrolysis of biological polymers into monomers (glycosides, fatty acids, amino acids) by an hydrolytic microflora that can be either aerobic or facultatively or strictly anaerobic.

(b) Acidogenesis from monomeric compounds and intermediary compounds formed during fermentation (production of volatile fatty acids, organic acids, alcohols, H_2 and CO_2) by a fermentative microflora that can be either facultatively or strictly anaerobic.

(c) Acetogenesis from the previous metabolites by a syntrophic or homoacetogenic microflora.

(d) Methanogenesis from the simple compounds that can be used by methanogens (in particular $H_2 + CO_2$ and acetate) which constitutes the last step of the methanogenic fermentation.

About two thirds of the CH_4 produced in nature derives from the reduction of the methyl group of acetate and about one third from reduction of CO_2 with electrons from H_2 or formate (Ferry, 1992). Lesser amounts of CH_4 are produced by the oxidative and reductive dismutation of methanol or methylamines that are mostly encountered in marine sediments. Methanogenic organisms have also been described that produce CH_4 from dimethyl sulfide or reduce CO_2 with primary, secondary and cyclic alcohols as electron donors. All of the pathways of methyl group reduction to CH_4 are mentioned below:

I. Reduction of CO_2 to CH_4: The reduction of CO_2 to CH_4 with H_2 or formate as the electron donor (Eq. 2 and 3)

$$4\,H_2 + CO_2 \longrightarrow CH_4 + 2\,H_2O \quad \text{..........} \quad (2)$$

$$\Delta G^{0'} = -\,130.4 \text{ kJ mol}^{-1}\ CH_4$$

$$4\,HCOO^- + 4\,H^+ \longrightarrow CH_4 + 3\,CO_2 + 2\,H_2O \quad \text{..........} \quad (3)$$

$$\Delta G^{0'} = -\,119.5 \text{ kJ mol}^{-1}\ CH_4$$

Carbon dioxide reduction pathway is derived mostly from studies with *Methanobacterium thermoautotrophicum* strains although they are classified as strains of the same species, the fact that they are only distantly related may explain some differences reported between them. Studies with these organisms have revealed several novel cofactors involved in the CO_2-reduction pathway and other pathways for methanogenesis.

II. Conversion of acetate to CO_2 and CH_4 : The conversion (Eq. 4) is restricted to *Methanosarcina* and *Methanothrix*.

$$CH_3COO^- + H^+ \longrightarrow CH_4 + CO_2 \quad \text{..........} \quad (4)$$

$$\Delta G^{0'} = -\,36 \text{ kJ mol}^{-1}$$

In both genera, acetate is activated to acetyl Co-A followed by decarboxylation and methyl transfer to HS-CoM. The reductive demethylation of CH_2 - S - CoM to CH_4 is similar to that described for CO_2 - reducing species that electrons for reduction of CoM - S-s - HTP derive from oxidation of the carbonyl group of acetate to CO_2. In nature, the major substrates for CH_4 production are acetate and H_2+CO_2 and also a few other organic compounds (Table 2).

TABLE 2. *Major substrates for methane production and the trophic groups*

Trophic Group	Substrate utilized
Hydrogenotrophs	$H_2 + CO_2$
Formatotrophs	Formate
Acetotrophs	Acetate
Methylotrophs	Methylated compounds
Alcoholotrophs (no strict forms)	Alcohols I, II

Many of the anaerobic methanogens, utilizing acetate as a C source, use hydrogen as their electron donors. The consumption of H_2 by the methanogens is often important in maintaining low enough H_2 partial pressures to permit active growth of acetogenic bacteria that produce H_2, yet are inhibited by its accumulation. This phenomenon of "interspecies H_2 transfer" is important in many anaerobic systems. It was observed that no H_2 accumulates during active methanogenesis, but if methanogens are inhibited by specific inhibitors, H_2 accumulates. This suggests that H_2 is an important and perhaps limiting energy source for the CH_4-producing bacteria.

Methanotrophy

Like nitrification-denitrification and sulfur oxidation - sulfate reduction, methanotrophy is the other part of the coupled reaction of methanogenesis and involves the conversion of methyl group to CO_2, using either oxygen or other compounds of higher oxidation status as electron acceptors. Bacteria that are able to grow using CH_4 are referred to as methanotrophs and are part of a larger grouping of organisms that can utilize one-carbon (1-C) compounds having no C-C bonds. Methanotrophic bacteria isolated and investigated so far uses molecular oxygen as the terminal electron acceptor and therefore are obligate aerobes, although there is evidence that certain, mostly SO_4^{2-}-reducing habitats exist in which anaerobic CH_4 oxidation occurs.

Aerobic methane oxidation

The enzyme responsible for the initial step in CH_4 oxidation is a monooxygenase enzyme that requires molecular O_2. The product of this reaction, methanol, is further successively oxidized via formaldehyde to formate and then CO_2. There is some evidence that some of these intermediates may leak or be excreted from cell and perhaps support growth of other bacteria. The use of enzymes known as methane monooxygenases to catalyze the oxidation of CH_4 to methanol is a defining characteristic of methanotrophs. The common metabolic pathway, branches off, depending upon the type of methanotrophs, the monoxygenase involved, the metabolism of substrates by methanotrophs, the central role of formaldehyde as an intermediate in catabolism and anabolism and the unique pathways employed for the synthesis of intermediates of central metabolic route. Formaldehyde is usually assimilated further either through RuMP pathway or Serine pathway. Yeast strains that grow on methanol utilize another pathway known as the dihydroxyacetate pathway for formaldehyde assimilation. Methane monooxygenases present in aerobic methanotrophic bacteria exhibit a striking lack of substrate specificity, resulting in the fortuitous metabolism of a very large number of compounds including xenobiotic chemicals. Because of the ability of methanotrophs to catalyze a large number of biotransformations, they have attracted the interest of scientists involved in the development of bioremediation technologies and in the use of bacteria containing methane monooxygenases for the production of chemicals with commercial value.

Anaerobic methane oxidation

Several studies have confirmed that CH_4 is also consumed in other anaerobic environments, including anoxic marine water, sediments of soda lakes and freshwater sediments. In vertical profiles of marine sediments, methane oxidation and sulfate reduction occur coincidentally. Although repeated attempts to isolate CH_4-oxidizing anaerobes in pure culture have failed, sulfate dependent methane oxidation (SDMO) has been accepted to occur in nature. Coupled with the poor thermodynamic yield of SDMO, this has led to the idea that CH_4 oxidation under anaerobic conditions is a co-metabolic activity and that the responsible organism(s) do not conserve energy from the process. Anaerobic CH_4 oxidation has frequently been determined by measuring the conversion of $^{14}CH_4$ to $^{14}CO_2$ which is trapped in alkaline solutions. In nearly all cases, net CH_4 consumption was not demonstrated in culture studies.

Methane oxidation and rice plants

Methane emission is the net balance of two opposite processes i.e. CH_4 production and its oxidation. In soil 58-80% of locally produced CH_4 is oxidized. The rate of CH_4 oxidation is often higher in rice-planted soil than in unplanted one. Such oxidation rate varies with rice growing stages. For example, about 36.5 and 54.7% of CH_4 is oxidized at tillering and panicle initiation stages respectively. Oxidation at harvesting and ripening stage is, however, negligible.

Root oxidation power as measured by oxidation of alpha-naphthylamine decreases when the roots grow older. It differs greatly among cultivars. If rice cultivars have similar root weights, those with high oxidative capacity are ideal for mitigating CH_4 emission.

Rice plants influence CH_4 oxidation in 2 ways, i.e. by diffusion of atmospheric O_2 via aerenchyma into the rhizosphere, and by enzymatic oxidation as measured by N flush inhibition technique and alpha-naphthylamine oxidation method. The pore size of aerenchyma is the main plant parameter that controls O_2 transport through the plant to the rhizosphere, and it's often shows a positive correlation with O_2 concentration in the rhizosphere. Several factors have been reported to affect the O_2 release from the rice roots. For instance, metabolic inhibitors such as DNP, NaN_3 and KCN could increase the O_2 release rate. The soil redox potential (Eh) could also influence the process.

The development of aerenchyma is determined by the intensity of anaerobiosis. For example, the development of aerenchyma in plants at a soil Eh of –250 ± 10 mV as compared to plants under well-aerated conditions (515 ± 25 mV). As results of enlarged aerenchyma, the root porosity was increased to 41.4% in the flooded plants as compared to only 13.3% in non-flooded or drained plants. Increased porosity enhance the transport of O_2 from the atmosphere to the roots; O_2 loss from the roots increased to 4.6 mmol O_2 $g^{-1}day^{-1}$ in the flooded plants as compared to only 1.4 mmol $g^{-1}day^{-1}$ in drained plants. The supply of O_2 by the plants to the rhizosphere often stimulates high activities of CH_4-oxidizing bacteria in the vicinity of rice roots.

Different rice cultivars can support different rates of CH_4 oxidation by developing variable root porosity and oxidation powers. It was found that at the tillering stage, the root air spaces were small and did not vary among the rice cultivars. But at later stage they varied greatly. Several experiments indicated that up to 40% of the potential CH_4 flux could be oxidized in the rhizosphere. Indirect assessments suggested that 50-90% of the CH_4 transported to the rhizosphere of the rice plants is oxidized. Even though recent results indicate the presence of methanotrophic activity associated with roots and to a lesser extent lower parts of the stem, the significance of CH_4 oxidation during the passage through the rice plants is still unknown.

Aerenchyma and mechanisms of methane transport through rice plants

The primary function of aerenchyma formation in hydrophilic plants, including rice, is the delivery of O_2 to the roots, but several gases are also transferred through them in the reverse direction. They are predominantly responsible for plant-mediated transfer of CH_4 from paddy fields to the atmosphere. Aerenchyma in rice plants is composed of small, medium and large size lacunae. Both amount and density of large aerenchyma lacunae exhibited highly significant correlation suggesting that they control methane transport capacity (MTC) of rice plants.

Aerenchyma formation in rice plants is a varietal character - in some varieties it is well developed while in others it is not so. It develops with the advancement of plant growth. Its development is also affected by the Eh of the rhizosphere; large aerenchyma develops in response to highly reduced conditions. Wide difference in gas transport capabilities of different cultivars is mainly due to variations in type and amount of aerenchyma.

At the seedling stage (plant age 25 days), MTC is lowest; it increases by a factor of about 6 and 8 at the early tillering stage (35 days old) and maximum tillering (50 days old), respectively. Plants at panicle initiation (60 days old) show maximum MTC and further growth to the flowering stage (80 days old) does not change the MTC. However, there is a significant decrease in MTC at maturing. Such decrease at maturity appears to be due to collapse of large aerenchyma lacunae and a concomitant blockage of aerenchyma channels. The path of CH_4 through the rice plant involves the following steps: diffusion into the root, conversion to gaseous CH_4 in the root cortex, diffusion through cortex and aerenchyma, and release to the atmosphere through microspores in the leaf sheaths. The dissolved CH_4 in soil water diffuses into surface water of roots and cell-wall water of root cortex. Such transfer is driven by concentration gradient. Cracks in the junction point of the main root and root hairs are, however, the predominant entrance ports for CH_4 from surrounding soil solution to the aerenchyma. The roots can also absorb as much in gaseous form.

Methane is released to the atmosphere mainly through micropores in the leaf sheaths in the lower leaves but not from stomata. Use of ^{13}C labeled CH_4 demonstrated that although CH_4 is transported by the rice plants predominantly via molecular diffusion, a small component is also due to transpiration - induced flow.

Most of the CH_4 released is channeled through the culm, which is an aggregation of leaf sheaths. The aerenchyma channels of primary roots showed direct connection with those of culms and are the main conduit for CH_4 emission. About 50% of the CH_4 is released from leaf blades before shoot elongation, whereas only a small amount is emitted through leaves, as plants grow older. In addition to the presence of micropores on the leaf sheaths, cracks at the junction of internodes are also found sometimes to facilitate CH_4 transport. Methane can also be released from panicles particularly when vegetative parts are submerged. Root-shoot transition zone is, however, the main site of resistance to plant-mediated CH_4 exchange. Relative difference in CH_4 flux between two varieties of rice is mainly due to variation in their transfer capacity through pore diameter of the root-shoot zone, rather than to production of CH_4 or its oxidation.

Rice cultivars having higher number of tillers increases the CH_4 emission rate. It is presumably due to the proportional enhancement in channels/outlets of aerenchyma for the upstream transport of CH_4. Tiller number can thus, become a major controlling factor of plant-mediated CH_4 transport in widely different cultivars. Therefore, plants with less number of tillers would minimize the CH_4 transport from the soil to the atmosphere. Rice cultivars with few unproductive tillers, small root system, high root oxidative activity and high harvest index are ideal for mitigating CH_4 emission in rice fields.

Factors for methane production

Methane emission from rice fields

Methane emission show pronounced variations among the rice growing sites of world, even under identical crop management. Continuous flooding, pure mineral fertilizer and cultivar types have pronounced influence on CH_4 emission (Wassmann et al., 2000b) (Table 3).

Methane emission varied from 14 to 375 mg m^{-2} d^{-1} in most rice growing areas in the world. It is affected by water regimes, soil amendments, cultivars and type of fertilizers used. In India the mean CH_4 emission from rice field ranged from 3.5 to 4.2 Tg yr^{-1}(Mitra, 1992; Parashar, 1996). The

TABLE 3. *Contribution of plant-mediated methane emission under different treatments*

Fertilizer/ Cultivar	Plant age or interval	Overall CH_4 emission rate (mg CH_4 m^{-2} h^{-1})	Plant mediated CH_4 emission (% of overall emission)
Urea/Roma	25 days	7.8	0
Urea/Roma	54 days	17.0	48
Urea/Roma	76-103 days	23-28	90-97
Unfertilized/Roma	Single season	11.0	88
Unfertilized/Lido	Single season	8.1	90
Urea/IR 72	Dry season	1.1	85
Straw/IR 72	Dry season	9.4	65
Urea/IR 72	Wet season	1.3	82
Straw/IR 72	Wet season	6.3	48

average CH_4 emission from rainfed tropical rice ecosystem in India was reported as 32 kg ha^{-1} yr^{-1} (Adhya et al., 2000). As the systems with high GWP are restricted to rice field with long flooding periods and considerable amount of organic inputs, the GWP of these systems are driven by CH_4 emission. Irrigated continuously-flooded rice paddy showed a CH_4 flux value of 4-26 mg m^{-2} hr^{-1} and 0.7-4.7 Gg ha^{-1} per cropping season of 75 days (Adhya et al., 1994). Bhatia et al. (2004) estimated the CH_4 flux from different states of India using the IPCC default value and concluded with an emission of 4.7 Tg yr^{-1}.

Effect of soil amendments on methane emission

Seasonal flux of CH_4 was high following the application of fertilizer-N and organic amendments (Fig. 3). All the organic treatments in combination with urea affected higher CH_4 flux over that of chemical-N (urea) alone. Over the season, the ranking in emission from the four treatments was green manure (GM) (212% increase as compared to urea alone) > blue green algae (BGA) (61%increase) > FYM (54%increase) > urea (Adhya et al., 2000). Organic matter amendment enhanced the readily mineralizable soil organic carbon which is the main source of fermentation products in flooded soils and sediments that are driven to CH_4 by strict anaerobic bacteria (methano-gens).

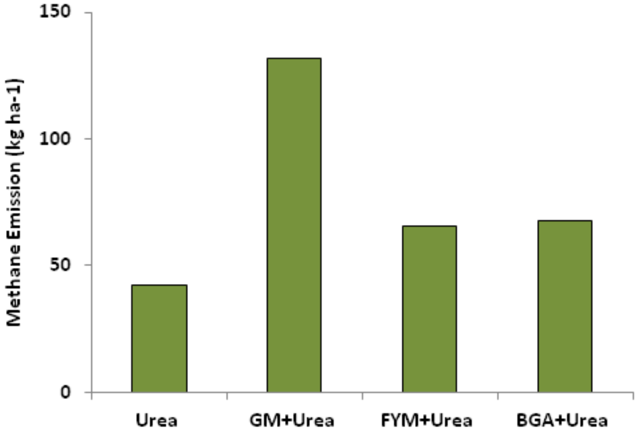


FIGURE 3. *Methane emission from a rainfed alluvial field planted to rice (cv. CR 749-20-2) under the influence of urea N in combination with different organic amendments*

Effect of water regime on methane emission

Flooding the soil creates anaerobiosis and conditions favourable for CH_4 production and emission. Thus floodwater regime can have a strong influence on CH_4 emission rates from rice fields and a single mid season drainage is considered to reduce seasonal CH_4 emission rates by about 50%. Mean CH_4 emission was lowest in field plots that were alternately flooded as to continuously flooded (Fig. 4) field plots leading to a 15% reduction in seasonal CH_4 flux. Amendments with rice straw at 2 t ha^{-1} significantly increased CH_4 production under both continuously flooded and intermittently flooded fields.

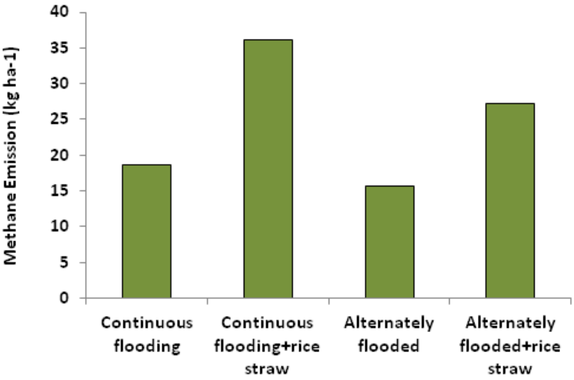


FIGURE 4. *Methane emission from a rainfed alluvial field planted to rice (cv. CR 749-20-2) as affected by water regime and straw amendments*

Cultivar variation

Rice plants serve as the major conduit for the transfer of CH_4 from the reduced soil layer to the atmosphere and more than 90% of the CH_4 fluxes from paddy soils are mediated by the rice plants. There are inherent variability in plant architecture, metabolic activity and gas transport potential among different rice cultivars. Among the four high yielding varieties tested, the degree of CH_4 efflux followed the order of Lalat > IR72> Gayatri > Tulasi (Fig. 5) (Adhya et al., 2000). Cultivar Gayatri and Tulasi had lower CH_4 flux, there by producing -13% and 22% lesser CH_4 than that of IR72. Wide variations among rice cultivars with regard to CH_4 flux opens up possibilities for breeding rice cultivars with low CH_4 emission potential.

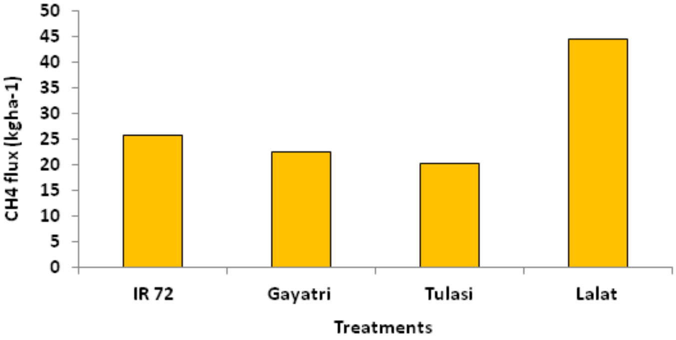


FIGURE 5. *Methane emission from a rainfed alluvial field planted to different rice cultivars under uniform conditions*

Root exudates of rice plants and methane production

Rice plants can influence soil Eh and thus CH_4 production by consuming O_2 from the rhizosphere (root respiration) and by enhancing the supply of electron donors i.e. easily decomposable organic substrate through root exudates, sloughed-off tissues and debris. On average, 30-60% photosynthesised C is allocated by plants to the roots and a substantial portion of this C is released or secreted by the roots in the form of organic compounds in the rhizosphere. These compounds constitute good food/energy materials for CH_4 producing organisms, methanogens.

Considering the enormous genotypic and phenotypic variations in the species *Oryza sativa*, large variation in the quantity (exudation rate) and quality (composition) of root exudates is observed (Table 4) (Aulakh et al., 2001)

TABLE 4. *Total organic carbon and organic acids added through root exudates of different rice cultivars*

Cultivar	Total organic C				Total organic acids [a]			
	Seedling	Panicle initiation	Flowering	Maturity	Seedling	Panicle initiation	Flowering	Maturity
				mg C g^{-1} soil [b]				
Dular	3.8	7.2	7.8	5.8	1.3	4.0	4.3	3.9
IR 72	2.9	9.7	9.2	4.9	1.1	5.6	5.5	2.9
IR 65598	1.9	4.4	5.3	3.4	0.8	2.9	3.8	2.4
B 40	1.8	7.6	c	c	0.7	4.6	c	c
IR 65600	2.0	3.8	c	c	0.8	1.9	c	c

a= total of lactic, formic, acetic, tataric, malic, oxalic, succinic and citric acid; b = on dry weight basis; c = treatment was not included

Root exudates contain both high-molecular-weight substances mainly mucilage and ecto-enzymes, as well as low-molecular-weight substances consisting of organic acids, phenols and amino acids. Total amounts as well as the proportion of different compounds in root exudates vary considerably due to various endogenous and exogenous factors such as growth stages of rice, mechanical impedance to its roots, presence of toxic elements, nutrient deficiencies and water status of growing medium (soil), etc. The exudation rates, in general, are lowest at seedling stage; increase until flowering but decreased at maturity (Table 4). Plants increase their exudation to improve their ability to tolerate toxic elements such as Pb, Cd, Al. Increased exudation is also associated with nutrient deficiencies and dry soil conditions for mobilizing soil nutrients. Among the organic acids released by rice roots, malic acid showed the highest concentration followed by tartaric, succinic, citric and lactic acids. With advancement of plant growth, exudation of organic acids substituted exudation of sugars (Aulakh et al., 2001).

Methane production and CH_4 emission are more closely related to the release pattern of root exudates C than its individual components. The proportion of exudates C converted to CH_4 ranged between 61 and 83% (Aulakh et al., 2001) (Table 5). The plant-derived CH_4 production

TABLE 5. *Proportion of added root exudate- carbon converted to methane in rhizosphere*

Cultivar	Proportion of added root exudate-C converted to CH_4 (%)			
	Seedling	Panicle initiation	Flowering	Maturity
21-d incubation				
Dular	65	65	72	73
IR 72	73	62	62	75
IR 65598	79	61	65	69
7-d incubation				
B 40	76	70	a	a
IR 65600	83	67	a	a

a = treatment was not included

rates corresponded to 17-40% of the CH_4 emission rates at flowering and maturity. Such plant-derived organic C would produce 3-4 fold greater amount of CH_4 during panicle initiation to flowering as compared to the seedling stages. It is, therefore, reasonable to speculate that plant-derived C possibly determines CH_4 production during later growth stage of rice.

An understanding of the quality and quantity of root exudates of rice during different growth stages and of widely used cultivars may thus help in selecting and breeding cultivars that have low root exudation and, as a consequence, results in reduced CH_4 emission from paddy fields. Since root exudation represents a possible loss of photosynthates from the plants, minimizing this process may also result in increased rice yield.

Mitigation options

Mitigation of carbo dioxide emissions

The increasing concentration of GHGs in the atmosphere, such as those of CO_2, CH_4, and N_2O are expected to contribute to global warming. Reducing the content of these gases has become a ''global commons'' issue (Ingram & Fernandes, 2001; Lal, 2004). The increase in the storage capacity of carbon (C) in agricultural soils through judicious land-use and appropriate management practices can mitigate the process of climate change (Wright et al., 2004).

On the other hand, CO_2 emission depends on the soil management, water management and cultivation methods and other agricultural management practices. No tillage or minimum tillage reduces CO_2 efflux from soil to the atmosphere rather than conventional tillage resulting into more C sequestration in soil. Prolonged existence floodwater in rice soil creates anaerobic environment which helps in slow decomposition of soil organic matter and the overlying water acts as a diffusion barrier to liberated CO_2 from soil to the atmosphere, thereby storing more carbon as compared to aerobic rice system. In a rice-maize-legume cropping system, legume cultivation reduces CO_2 emission from soil as compared to maize cultivation, which, in turn, helps to store more soil-C leading to soil-C sequestration. The aerobic rice cultivation system in upland condition is responsible for higher CO_2 emissions than lowland flooded rice soils and in case of CH_4 emission the scenario is just opposite.

Mitigation of methane emissions

The increase in CH_4 contributes to the global warming and effects the atmospheric chemical changes. Rice plants are implicated in CH_4 production, oxidation and transportation. In order to reduce the CH_4 emissions from rice fields various researchers suggested options for mitigation. Large number of studies from various countries indicated the possibility of substantial reductions in CH_4 emissions from actual field situations. The options available differ from the practices that are followed which include management of the crop, soil and irrigation requirements, varietal choice, and agrochemical usage. The contributions of options that are available towards the reduction of CH_4 emission largely depend upon the situations and component factors. Mitigation options are broadly related to the following activities:

- ☐ adoption of different rice cultivars
- ☐ field management
- ☐ applications of different agrochemicals
- ☐ organic residue management
- ☐ irrigation schedules
- ☐ crop protection and microbial manipulations

Mid-season drainage substantially reduced CH_4 emissions by about 30-50% as compared to continuous flooding or waterlogging . The practice of intermittent irrigation or cycles of alternate flooding and drying as occur in rainfed rice situations led to significant reductions in the CH_4 emissions from rice fields. Acid sulphate soils had minimum emission rates compared to other soils. Methane emission rates were higher from transplanted rice than from direct sown. Direct seeding on dry soil had least CH_4 emission, followed dry direct seeding on wet soil. The age of seedlings at the time of transplanting also had significant impact on subsequent CH_4 emission (8 day old seedling had higher CH_4 than the 30 day old seedlings) probably because of the larger cultivation period of the former treatment. Thus, methane emissions from 30-day old transplanted seedlings, direct seeding on wetland soil and direct seeding on dry soil were reduced by 5%, 13% and 37%, respectively (Ko & Kang, 2000).

The proper selection of rice cultivars is a potential mitigation option of methane emission. Rice cultivars with low CH_4 emission potential may be selected. Land management in the winter crop season significantly influenced CH_4 fluxes during the following flooded and rice growing period (Knox et al., 2000). Methane flux from plots planted to alfalfa (legumes) in the winter crop season was significantly higher than those obtained with treatments involving winter wheat or dry fallow. Land management practices in the winter crop season also affected temporal variation patterns of CH_4 fluxes and soil Eh after flooding.

Water management in the preceding crop season becomes crucial factor in influencing CH_4 emission from rice fields. The application of rice straw, which undergoes aerobic decomposition during winter crop season after incorporation, greatly reduces the subsequent CH_4 emission during following flooded and rice growing period. Rice straw and possibly green manure application at a suitable application time not only sustains soil fertility but also prevents the emission of large amounts of methane.

The influence of crop on seasonal CH_4 emissions is considerable and large part of this originating from the rhizodeposition of the current crop. The adoption of new varieties with reduced CH_4 emission could be a more profitable mitigation option. As rhizodeposition contributes about 37% of the total substrate (Cao et al., 1996), reduction of the rates of rhizodeposition, therefore, would be beneficial to both yield and reduced CH_4 emissions. Seasonal emissions could be decreased with the increase in the temperatures and shortened crop production. The diurnal variations in emissions are strongly correlated to temperature and moisture. The seasonal CH_4 emission in the wet season was about 2-3 times as much as that in the dry season. This is particularly explained by the higher daily mean temperatures in the wet season.

Application of rice straw has enhanced CH_4 emission. Rice straw compost resulted in a six fold reduction in CH_4 emission compared with uncomposted rice straw. The application of green manure rather than rice straw would be desirable to improve fertility status on one hand and decrease CH_4 emissions on comparable basis. The application of sulphate fertilizers has been suggested as a suitable option to reduce CH_4 emissions by increasing the size of the soil pool of alternative electron acceptors. Emission reductions to the tune of 50% were observed when SO_4^{-2} was applied to soil systems. The partial competition of the sulphate-reducing bacteria with methanogens for C substrate plays an important role. Seasonal methane emissions are sensitive to percolation rates in the range of 0 to 4 mm d^{-1}. High percolation rates and the necessary high frequency of irrigation could influence CH_4 emissions either by increasing the flux of O_2 dissolved in the irrigation water into the soil or by transport of CH_4 produced downward into groundwater, preventing it from being emitted. Possibly, the methanogenic substrates also move away from being acted upon by the methanogens.

Application of single super phosphate and potassium fertilizer led to the decrease cumulative seasonal CH_4 emissions. Results clearly indicated the role of sulphur content in the single super phosphate decreasing the CH_4 emissions. Also, potassium has a role in maintaining higher levels of oxidation status in the top soil profile encouraging oxidation processes in the rhizosphere and other regions affected by plants.

Several pesticides are reported to have influence on CH_4 production in soils systems. Though these agrochemicals are applied to the system as plant protection measures, studies indicate their role in mitigating the CH_4 production and its resultant emission (Sethunathan et al., 2000).

Compounds like carbofuran, hexachlorocyclo- hexane, butachlor, etc. had proven potential to reduce CH_4 production. Also some of the nitrification inhibitors have been shown to have potential to reduce CH_4 emissions. Methane emission from rice fields and the possible mitigation options should be evaluated within the perspective of overall context of rice cultivation of the region and ecosystem. The practices, depending upon their suitability and adoption, should be an integral part of the rice production system. This would, in the long run, serve to protect the environment through reduced emission as well as improve the crop yield.

Conclusions

World climate is not only a function of atmospheric physics but of atmospheric chemistry as well. In fact, the composition of the atmosphere is presently changing in a direction that ultimately may alter the global and regional climate. There is considerable concern over the increasing concentrations of atmospheric trace gases, such as CO_2, CH_4 and N_2O in view of their acknowledged role in atmospheric chemistry, both in the troposphere and stratosphere, through various photochemical interactions and the consequential climate change. With the intensification of agriculture and industry to sustain the demands of the growing billions, the contribution of greenhouse gases to global change is anticipated to increase. Atmospheric scientists predict that changes in the concentrations of these gases will have dramatic consequences for the habitability of our planet. Rice paddies are an important man-made ecosystem for the global C budget. The various controls of CH_4 emission from this ecosystem depend on the structure of plant and microbial communities and their interactions within the physical and chemical limits of soil environments. Further research is warranted to characterize these ecologies in relation to microbial- and other organismal communities and to identify the soil management options for manipulating the activities of methanogenic - and methanotrophic communities with dual objectives of increasing productivity and environmental quality.

References

Adhya, T.K., Bharati, K., Mohanty, S.R., Ramakrishnan, B., Rao, V.R., Sethunathan, N., & Wassmann, R. (2000). Methane emission from rice fields at Cuttack, India. *Nutrient Cycling in Agroecosystems,* 58, 95-105.

Adhya, T.K., Rath, A.K., Gupta, P.K., Rao, V.R., Das, S.N., Parida, K., Parashar, D.C., & Sethunathan, N. (1994). Methane emission from flooded rice paddy fields under irrigated condition. *Biology and Fertility of Soils,* 18, 245-248.

Alberto, R., Carmelita, Ma., Wassmann, R., Hirano, T., Miyata, A., Kumar, A., Padre, A., & Amante, M. (2009). CO_2/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the Philippines. *Agricultural and Forest Meteorology,* 149, 1737-1750.

Aulakh. (2001). Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant and Soil,* 230, 77-86.

Bhatia, A., Pathak, H., & Aggarwal, P.K. (2004). Inventory of methane and nitrous oxide emissions from agriculture soils of India and their global warming potential. *Current Science,* 87, 317-324.

Bouwman, A.F. (1990). Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. In A.F. Bouwman (Ed.), *Soil and greenhouse effect.* (pp. 61-127). New York, USA: John Wiley & Sons.

Cao, M., Gregson, M.S., Dent, B., & Heal, O.W. (1996). Global methane emission from rice paddies. *Chemosphere,* 55, 879-897.

Davidson, E.A., Savage, K., Verchot, L.V., Navarro, R. (2002). Minimizing artifacts and biases in chamber-based measurements of soil respiration. *Agricultural and Forest Meteorology,* 113, 21-37.

Denman, K.L., Brasseur, G., & Chidthaisong, A. (2007). Coupling between changes in the climate system and biogeochemistry. In S. Solomon, D. Qin, M. Manning, Z. Chen (Eds.), *Climate change 2007: The physical science basis.* (pp. 499-587). Cambridge and New York: Cambridge University Press.

Directorate of economics and statistics (DOES), Department of agriculture and cooperation, Ministry of agriculture (MOA), Government of India (GOI), (2011). http://agricoop.nic.in/agristatistics.htm

Ferry, J.G. (1992). Biochemistry of methanogenesis. *Critical Reviews in Biochemistry and Molecular Biology,* 27, 473-503.

Hill, P.W., Marshall, C., Harmens, H., Jones, D.L., & Farrar, J. (2004). Carbon sequestration: Do N inputs and elevated atmospheric CO_2 alter soil solution chemistry and respiratory C losses?. *Water Air and Soil Pollution,* 4, 177-186.

Houghton, J.T., Meir-Filho, L.G., Callander, B.A., Harris, N., Katerberg, A., & Maskel, K. (1996). *IPCC report on climate change: The science of climate change. WG I contribution to the IPCC second assessment report on methane emission from rice cultivation.* Cambridge, UK: Cambridge University Press.

Ingram, J.S.I., & Fernandes, E.C.M. (2001). Managing carbon sequestration in soils: Concepts and terminology. *Agriculture Ecosystem and Environment,* 87, 111-117.

Intergovernmental Panel on Climate Change (IPCC). (1995). *Climate change 1995: The science of climate change*. In J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, K. Maskell (Eds.), Cambridge: Cambridge Univ. Press.

Intergovernmental Panel on Climate Change (IPCC). (2007). Climate change-synthesis report. In *An assessment of the Intergovernmental Panel on Climate Change*. Plenary XXVII. 12-17, November, Valencia, Spain, pp. 52.

Knox, J.W., Matthews, R.B., & Wassmann, R. (2000). Using a crop/soil simulation model and GIS techniques to assess methane emissions from rice fields in Asia. III. databases. *Nutrient Cycling in Agroecosystems,* 58, 179-199.

Ko, J.Y., & Kang, H.W. (2000). The effects of cultural practices on methane emissions from rice fields. *Nutrient Cycling in Agroecosystems*, 58, 311-314.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science,* 304, 1623-1627.

Mills, R., Glanville, H., McGovern, S., & Emmett, B. (2011). Soil respiration across three contrasting ecosystem types: Comparison of two portable IRGA systems. *Agricultural and Forest Meteorology,* 174, 532-535.

Minami, K., & Neue, H.U. (1994). Rice paddies a methane source. *Climate Change,* 27, 13-26.

Mitra, A.P. (1992). Greenhouse gas emission in India. 1991 - Methane Campaign. Scientific Report No. 2. Council of Scientific and Industrial Research (CSIR) and Ministry of Environment and Forest (MoEF), New Delhi.

Neue, H.U. (1997). Rice growing soils: Constraints, utilization and research needs. In *Classification and management of rice growing soils.* Proceedings of the fifth International soil management workshop, Taiwan. p. 1-14.

Parashar, D.C., Mitra, A.P., Gupta, P.K., Rai, J., Sharma, R.C., Singh, N., Kaul, S., Lal, G., Chaudhay, A., Ray, H.S., Das, S.N., Parida, K.M., Rao, S.B., Kanungo, S.P., Ramasami, T., Nair, B.U., Swamy, M., Singh, G., Gupta, S.K., Singh, A.R., Saikia, B.K., Barua, A.K.S., Pathak, M.G., Iyar, C.P.S., Gopalkrishnan, M., Sane, P.V., Singh, S.N., Banerjee, R., Sethunathan, N., Adhya, T.K., Rao, V.R., Palit, P., Saha, A.K., Purkait, N.N., Chaturvedi, G.S., Sen, S.P., Sen, M., Sarkar, B., Banik, A., Subbaraya, B.H., Lal, S., Venkataramani, S., & Sinha, S.K. (1996). Methane budget from paddy fields in India. *Chemosphere,* 33, 737-757.

Prentice, I.C., Farquhar, G.D., Fasham, M.J.R. (2001). The carbon cycle and atmospheric carbon dioxide. In J.T. Houghton, Y. Ding, D.J. Griggs (Eds.), *Climate change 2001: The scientific basis.* (pp. 183-238). Cambridge and NY: Cambridge University Press.

Sethunathan, N., Kumaraswamy, S., Rath, A.K., Ramakrishnan, B., Satpathy, S.N., Adhya, T.K., & Rao, V.R. (2000). Methane production, oxidation, and emission from Indian rice soils. *Nutrient Cycling in Agroecosystems,* 58, 377-388.

Tseng, H.K., Tsai, L.J., Alagesan, A., Tsuang, J.B., Yao, H.M., & Kuo, H.P. (2010). Determination of methane and carbon dioxide fluxes during the rice maturity period in Taiwan by combining profile and eddy covariance measurements. *Agricultural and Forest Meteorology,* 150, 852-859.

Wassman, R., Neue, H.U., Lantin, R.S., Makarim, K., Chareonsilp, N., Buendia, L.V., & Rennenberg, H. (2000a). Characterization of methane emissions from rice fields in Asia. II. Differences among irrigated, rainfed, and deepwater rice. *Nutrient Cycling in Agroecosystems,* 58, 13-22.

Wassmann, R., & Aulakh. (2000). The role of rice plants in regulating mechanisms of methane emissions. *Biology and Fertility of Soils,* 31, 20-29.

Wassmann, R., Neue, H.U., Lantin, R.S., Buendia, L.V., & Renneberg, H. (2000b). Characterization of methane emissions from rice fields in Asia. I. Comparison among fields sites in five countries. *Nutrient Cycling in Agroecosystems,* 58, 1-12.

Wright, A.L., Hons, F.M., & Rouquette, F.M. (2004). Long-term management impacts on soil carbon and nitrogen dynamics of grazed Bermuda grass pastures. *Soil Biology and Biochemistry*, 36, 1809-1816.

XiuE, R., QinXue, W., ChengLi, T., JinShui, W., KeLin, W., YongLi, Z., ZeJian, L., Masataka, W., & GuoYoung, T. (2007). Estimation of soil respiration in a paddy ecosystem in the subtropical region of China. *Chinese Science Bulletin,* 52, 2722-2730.

*****

Chapter 4

Nitrous oxide emission from rice and rice based production system and its mitigation strategy

Sangita Mohanty*, A.K. Nayak, P. Bhattacharyya, Anjani Kumar, V. Kasthuri Thilagam and Annie Poonam
Central Rice Research Institute, Cuttack, Odisha, India
*email: sangitamoha@gmail.com

Nitrous oxide (N_2O), with a global warming potential of 298 times more than the carbon dioxide (CO_2) and longer atmospheric lifetime (approximately 120 years) is an important green house gas (GHG) and accounts for about 19% of total global warming effect. Apart from being a major GHG, it is an important air pollutant. On reaction with oxygen, N_2O gives rise to nitric oxide (NO), and NO in turn reacts with ozone, as a result, it is the main naturally occurring regulator of stratospheric ozone. Global average atmospheric concentrations of N_2O have increased from about 270 parts per billion by volume (ppbv) in 1750 to 314 ppbv in 1998, which equates to a 16% increase for the period. In the last two decades, atmospheric concentrations of N_2O continue to increase at a rate of 0.25% per year (IPCC, 2007).

Rice is the main source of food for about half of the world's population. It is cultivated in more than hundred countries. Rice along with wheat and maize accounts for about 60% of total global N consumption, irrigated rice alone consumes about 8 to 9 million tons of fertilizer N annually, which is about 10% of total N production in the world. In general, in Asia 60-150 kg N ha^{-1} is applied per crop but because of poor N recovery efficiency (30-40% even lower) most of the N is lost through various mechanisms like volatilization, denitrification and leaching. Hence, rice systems are major contributor to the accumulation of reactive N compounds in the environment and significant source of emission of N_2O to the atmosphere.

Sources of nitrous oxide

TABLE 1. *Global nitrous oxide emission (Tg N yr^{-1}) from different sources (Adopted from Denman et al., 2007)*

Sources	N_2O emission (Tg N yr^{-1})
Natural	11
Soil	6.6 (3.3–9.0)
Ocean	3.8 (1.8–5.8)
Atmospheric chemistry	0.6 (0.3–1.2)
Anthropogenic	6.7
Energy, industry, biomass burning	2.0 (0.7–3.7)
Agriculture	4.7 (2.3–8.0)
Total	17.7 (8.5–27.7)

Denman et al. (2007)

Nitrous oxide in atmosphere is produced both from natural and anthropogenic sources. Natural emissions of N_2O primarily results from bacterial breakdown of nitrogen in soils and in the earth's oceans. Based on the available data globally (Table 1), soils covered by natural vegetation are estimated to produce 6.6 Tg of N_2O annually and oceans are thought to add around 3.8 Tg of N_2O annually to the atmosphere. Together, these two sources account for about 60% of the natural sources. Whereas anthropogenic activities like agricultural soil management, fossil fuel combustion, nitric acid production, livestock manure management, human sewage, adipic acid production, etc., are responsible for about 30% of total N_2O emission; apart from that anthropogenic activities are the main driver behind the N_2O emission from oceans and estuaries through their contribution of nitrogen to water bodies, however exact quantification of that contribution is not available. Many microbiological, chemical, physical factors affect the emission and a complex interaction among them makes the extrapolation of global budget uncertain and difficult.

Contribution of agriculture to global nitrous oxide emission

Agriculture directly and indirectly contributes significantly to global N_2O emission. There are considerable differences (65-96%) in the estimated share of agriculture in total anthropogenic source of N_2O emission (Mosier et al., 1998; Bouwman et al., 2002; Denman et al., 2007). There are three distinguished sources of agricultural N_2O emission: direct N_2O emissions from fertilized agricultural soils, direct N_2O emissions from animal production and indirect N_2O emissions from nitrogen (N) used in agriculture (Mosier et al., 1998). Recently Syakila & Kroex (2011) estimated the N_2O emission from agriculture (Table 2) using revised emission factor from the IPCC 2006 guidelines (IPCC, 2006) and observed, the share of agriculture to the total anthropogenic source is 60%, lower than the earlier estimation of 80% in 1999 budget (Kroeze et al., 1999).

TABLE 2. *Global nitrous oxide emission (Tg N yr^{-1}) from agriculture in 2006 as estimated following IPCC 2006 guidelines*

Direct emission from agriculture	N_2O (Tg N yr^{-1})
Synthetic fertilizer	0.9
Animal waste	0.4
Biological N_2 fixation	0.1
Crop residue	0.3
Cultivated Histosol	0.1
Total	1.8
Animal production	
Animal waste management system	2.3
Indirect emissions	
Atmospheric deposition	0.4
Nitrogen leaching and runoff	0.6
Human sewage	0.3
Total	1.3
Total emission from agriculture	5.4

Emission of nitrous oxide from rice and rice based production systems

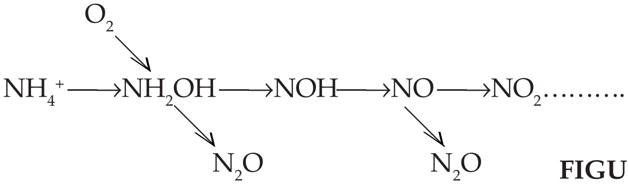
Rice is grown in a wide range of environments under diversified management practices. In general there are three major rice production systems: irrigated rice production systems, rainfed low land and rainfed upland production systems. Each system is different from the other with respect to varieties grown, methods of cultivation and soil and water management practices followed. Irrigated rice is grown in bunded fields with ensured irrigation for one or more crops a year; so that 5–10 cm of water can be maintained in the field. Irrigation is the main source of water in the dry season and is used to supplement rainfall in the wet season. In many humid tropical and subtropical areas, irrigated rice is grown as a monoculture with two or even three crops a year. Significant areas of irrigated rice are also grown in rotation with a range of other crops, including about 20 million ha of rice-wheat systems. Rainfed lowland rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season. Rainfed rice environments experience multiple abiotic stresses and high uncertainty in timing, duration, and intensity of rainfall. Up to 25% of total lowland areas suffer from uncontrolled flooding, ranging from flash floods of relatively short duration to deepwater areas that may be submerged under more than 100 cm of water for a few months. Widespread incidence of problem soils with poor physical and chemical properties is the constraints of production in this environment. Because of the environment prevailed, the farmers rarely apply fertilizer to the rice crop. Rainfed upland rice is grown under dryland mostly under direct seeded conditions. Upland environments are highly variable with respect to climate, soils type, and topography. Since rice production systems vary widely in their macro and micro environment, each system has its unique effect on carbon nitrogen dynamics in soil-plant-atmosphere continuum and hence there is wide spread variation in N_2O emission.

Mechanisms involved in production of nitrous oxide from rice field

Rice fields remain submerged for most part of the season. Presence of both aerobic and anaerobic layer, alternate wetting and drying cycles makes the rice production system a unique system in which both aerobic and anaerobic nitrogen metabolism take place in close proximity and with tight linkage. Unique physical, chemical and microbiological character of rice soil affects the N transformation process and emission of N_2O in different way than that observed in aerobic soil. Nitrous oxide is a byproduct of both denitrification and nitrification processes in soil. Nitrification is the main source of N_2O under aerobic conditions, while denitrification dominates under flooded rice fields. Denitrification is the microbial reduction of nitrate or nitrite form of N to dinitrogen or N oxides under anaerobic condition and presented as

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad \text{……….(1)}$$

Nitrification is the process of oxidation of ammonium form of N to nitrite or nitrate form and also responsible for the emission of N_2O from soil, though, the exact biochemical pathway of N_2O generation via nitrification is not clear. A series of path ways for the formation of N_2O via the intermediate compounds NH_2OH or NO has been proposed (Ritchie & Nicholas, 1972; Naqvi & Noronha, 1991).

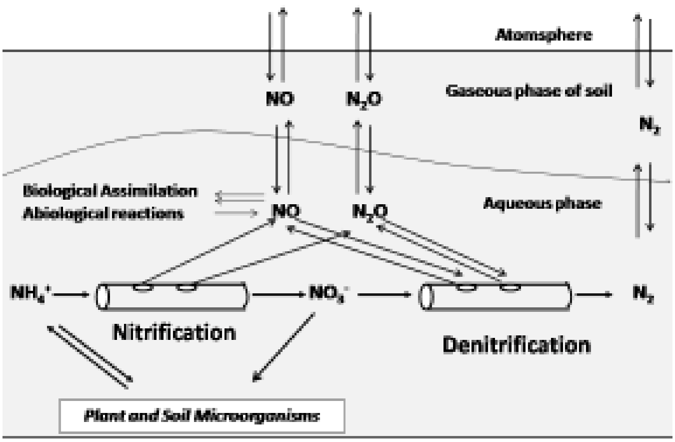


$$NH_4^+ \longrightarrow \overset{O_2 \searrow}{NH_2OH} \longrightarrow NOH \longrightarrow NO \longrightarrow NO_2 \text{………. (2)}$$
$$\qquad\qquad \searrow N_2O \qquad\qquad\qquad \searrow N_2O$$

Factors affecting nitrous oxide emission from soil

Several microbiological and ecological factors influences N transformation processes in soil and hence N_2O emission. Firestone & Davidson (1989) proposed "hole-in-the-pipe," model to explain the factors that regulate N_2O from soil. This model uses the analogy of a leaky pipe (Fig. 1) to suggest that there are two levels of control that regulate emissions of N_2O and NO from soil.

FIGURE 1. *Hole-in-the-pipe conceptual model*



First, the rate of nitrogen cycling through ecosystems which determines the amount of nitrogen flowing through the pipe and influences the total emission, second is the factors (soil, water content and others) that regulated the ratio of N_2O: NO, these factors are considered as the leakage of the pipe and their influence is symbolized by the relative size of the holes. In fertile soils, flow through the pipe is large, as are the "leaks". The converse is true in infertile soils, and neither gas is produced in large amounts. In dry soils, where O_2 is present, the nitrification "leak" is greater and NO, which is more oxidized than N_2O and N_2, is the dominant gas. In wetter soils, with less soil O_2, denitrification is dominant process and more N_2O is produced. In very wet soils denitrification process dominates, but N_2O further reduced to produce the end product, N_2 (Davidson et al., 2000).

Type and dose of nitrogenous fertilizer controls the amount of N flows through the system and hence influences the N_2O emission (Mosier, 1994; Cai et al., 1997). Increase in total N_2O emission with the increase in N application rate has been observed (Majumdar et al., 2000, Kumar et al., 2000). Soil water content regulates the transport of oxygen into soil and the transport of NO, N_2O, and N_2 out of soil, hence considered as the most important controller of these ratios. The relative contributions of nitrification and denitrification to NO, N_2O, and N_2 emissions could be expressed as a function of water filled pore space (Davidson et al., 2000). Relative abundance of electron donors (soil organic carbon) and acceptors (primarily oxygen, nitrate, and sulfate) also affects the relative proportions of N_2, N_2O, and NO emissions (Firestone, 1982; Firestone & Davidson, 1989). The rate of biological denitrification and the potential production of N_2O from soil depend upon the presence of readily metabolized organic matter and the availability of water soluble organic matter. In general, addition of degradable organic materials increases N_2O production in soils containing NO_3^- or applied with fertilizer NO_3^- (Murakami et al., 1987). The soil properties like texture, pH and salinity also reported to influence the emission of N_2O through their effect on nitrification and denitrification processes. In coarse-textured soils N_2O production exceeds up to 6-times in comparison to a heavy-textured soils. In the loamy soils, period of N_2O production lasted only 3 days, in the silty soils 10 days, while in the sandy soils about 21 days. High salinity inhibits both nitrification and denitrification (lnubushi et al., 1999). According to Menyailo et al. (1997), N_2O reductase is susceptible to salt, which may result in N_2O accumulation from denitrification under saline conditions. Nitrification is sensitive to extremes in soil pH. The optimal pH for nitrification is approximately 7 to 8 (Haynes, 1986). Laboratory incubations of soils added with NH_4^+ under aerobic conditions showed that N_2O production could increase by many times with increasing pH up to about 8 (Wang & Rees, 1996). At higher pH (pH >8.2), nitrite accumulates in soil, and this is then reduced to N_2O since competitive biological oxidation of nitrite by *Nitrobacter* is prohibited (Chalk & Smith, 1983).

Nitrous oxide emission from rice fields

There is wide spread variation in N_2O emission reported from rice field (Table 3). Denitrification is one of the important mechanisms for production of N_2O. Aulakh & Bahl (2001) estimated that 23 - 33% of the N applied through fertilizer is lost via denitrification during rice cropping. The study conducted at IRRI using ^{15}N tracer technique revealed magnitude of denitrification loss, may vary from negligible to 46% of the applied N depending on urea application and crop establishment methods (Buresh & De Datta, 1990). Fillery & Vlek (1982) reported that denitrification losses of fertilizer N were 5–10% in continuously flooded rice-cropped soils, while in the fallow soil the loss was around 40% of the applied N. Though N_2O is one of the by product of denitrification, continuous submergence condition may further reduce N_2O to N_2 so it has been generally thought that N_2O emission from rice field to atmosphere is very low or negligible. However studies showed N_2O was mainly emitted after the final water drainage for harvest (Chen et al., 1997; Tsuruta et al., 1997). With the current increasing trend in use of N fertilizer in rice with simultaneous increase in acreage, the total global emission is likely to increase appreciably. Bronson et al. (1997a) through an automated chamber sampling system observed N_2O fluxes in an irrigated rice system were generally negligible during the growing seasons, but small peaks (maximum 3.5 mgN_2O-N$m^{-2}d^{-1}$) appeared after N fertilizer applications, the N_2O flux increased sharply during the drainage period at mid-tillering until re-flooding, and seasonal flux was 2.5 times higher with ammonium sulphate than with urea. Higher N_2O flux (up to 80 mg N_2O-N$m^{-2}d^{-1}$) during fallow period due to nitrification of mineralized organic N in the topsoil and possibly from denitrification in the wet subsoil has been reported (Bronson et al., 1997b). Kumar et al. (2000) observed total N_2O-N emissions during crop growth season in an irrigated rice system ranged from 0.08% - 0.14% of applied N, it is 235 g N_2O-N ha^{-1} with application of ammonium sulphate and 160 g N_2O-N ha^{-1} with urea application. Nitrous oxide emissions were low during submergence and increased substantially during drainage of standing water.

Rainfed rice based production system occupies about 25% of the world's rice harvesting area. This system is characterized by alternate wetting and drying cycles as monsoonal rains come and go, hence potential for accumulation and denitrification of NO_3^- is high here (Abao et al., 2000). In this system the rice is grown during wet season followed by fallow or various upland crops in dry season depending upon the agro-climatic condition. Any time of the year rains can flood the soil resulting in denitrification and leaching of accumulated NO_3^-. Abao et al. (2000) observed low and negligible N_2O emission during the rice-growing season however the flux rose significantly as much as 2.5 mgN_2O-N$m^{-2}d^{-1}$ after fertilization events. During fallow period the emission continued at low level (< 2.5 mgN_2O-N$m^{-2}d^{-1}$), but rainfall events during fallow period resulted in increased emission to as high as 8 mgN_2O-N$m^{-2}d^{-1}$. Baruah et al. (2010) estimated the N_2O emission from rainfed rice environment ranged from 1.24 mg to 379.40 mgN_2O-N$m^{-2}d^{-1}$ depending upon the crop cultivar grown. Total seasonal N_2O emission ranged from 77 to 150 mgN_2O-N$m^{-2}d^{-1}$ and varieties with lower grain productivity but profuse vegetative growth, showed higher seasonal N_2O emission.

TABLE 3. *Total seasonal emission of nitrous oxide from rice fields in different locations under different crop management practices*

Production system	Location	N applied	Total N_2O emission	Reference
Continuous flooded	Hailun, China	95.4 kg N ha^{-1} (Urea)	0.06 g m^{-2}	Yue et al. (2005)
Intermittent Irrigation	Hailun, China	95.4 kg N ha^{-1} (Urea)	0.08 g m^{-2}	
Rice (saturated soil)	New Delhi, India	120 kg N ha^{-1}(Urea)	0.073 g m^{-2}	Pathak et al. (2001)
Rice (Intermittent drying)	New Delhi, India	120 kg N ha^{-1} (Urea)	0.09 g m^{-2}	
Irrigated Upland	New Delhi, India	120 kg N ha^{-1} (Urea) 120 kg N ha^{-1} (Ammonium Sulphate) 120 kgN ha^{-1} (Potassium Nitrate)	0.016 g m^{-2} 0.015 g m^{-2} 0.018 g m^{-2}	Ghosh et al. (2003)
Irrigated rice Flooding-mid season drainage-Flooding-Moist	Nanjing,Jiangsu province, China	150 kg N ha^{-1} (Urea) 300 kg N ha^{-1} (Urea) 450 kg N ha^{-1} (Urea)	0.26 g m^{-2} 0.44 g m^{-2} 0.61 g m^{-2}	Zou et al. (2005)
Irrigated Rice Flooding-mid season-reflooding	Jurong, China	100 kg N ha^{-1} (Urea) 200 kg N ha^{-1} (Urea) 300 kg N ha^{-1} (Urea	0.086 g m^{-2} 0.082 g m^{-2} 0.091 g m^{-2}	Cao et al. (1999)

Irrigated upland rice production systems are significant source of N_2O-N emission as soil is subjected to rapid drainage and upper layer of soil remains aerobic for most part of the season, both nitrification and denitrification processes contribute to the emission. Ghosh et al. (2003) estimated depending upon the application of N, total seasonal N_2O emission from upland irrigation system ranged f.rom 0.037 to 0.186 kg ha^{-1} which accounts for about 0.1-0.12% of applied N.

Nitrous oxide emission from rice-wheat system

Rice–wheat systems is the dominant cropping system in south Asia and covers about 32% of the total rice area and 42% of the total wheat area. Most of the rice–wheat cropping is fully irrigated. Under this system, farmers grow rice in the rainy season followed by wheat in winter. Rice is generally grown in flooded fields whereas the wheat crop requires well-drained soil conditions. This fundamental difference in the growing conditions creates a unique environment that influences the N dynamics differently in comparison to that observed in rice-rice system. The continuous submergence condition and anaerobic condition restricts nitrification processes and drying period during wheat season favours nitrification and NO^-_3 - N accumulated during wheat season, is subjected to losses by denitrification and leaching during flooding in subsequent rice cultivation (Pathak et al., 2001). Emission of N_2O-N from rice-wheat systems typical of farmers' field in Indo-Gangetic plains could vary between 654 and 1570 g ha^{-1} depending upon fertilizer application and irrigation. This accounts for 0.38% of applied N, where 240 kg N is applied annually.

Nitrous oxide emission from rice soil is controlled by the real-time field conditions and fluctuations in cultural practices. It is important to monitor N_2O emission from different rice ecosystems and estimate realistic regional and global budgets. Some attempts have been made to predict N_2O-emissions through simulation of soil N pathways. Using DNDC model, Pathak et al. (2005) predicted annual net emission of 0.04–0.05 TgN_2O-N from rice fields (42.25 million ha) of India under continuous flooding condition whereas it is higher (0.05–0.06 TgN_2O-N) under intermittent flooding condition .

Uncertainities in the estimation of nitrous oxide emission and research needs

Agronomic practices such as tillage and fertilizer applications can significantly affect the production and consumption of N_2O because of alterations in soil physical, chemical, and biochemical parameters. These factors interact and the magnitude of interaction results in the temporal and spatial variability in the emission of N_2O, hence the variability associated with estimation of N_2O emission is quite significant. Dobbie et al. (1999) observed 20-fold variation in annual N_2O flux at a grass land site between 1992 and 1998 mainly because of the rainfall around the time of fertilizer application. Field level emission data are used to upscale to regional, national and global level using default emission factors, and the methodologies recommended by the IPCC. The upscaling processes that depend highly on the models and database are responsible for about 63% uncertainties (Xuri et al., 2003).

Most of the reported data on field level N_2O-N emission are obtained from non-flow-through, non-steady-state (NFT-NSS) chambers (Bouwman et al., 2002). Deployment of chambers on soil surface changes energy balance of the enclosed soil surface, which in turn alters the soil and headspace temperatures. Changes in soil temperature may affect N_2O production, flux rate and concentration of gas; therefore, the emission of N_2O-N inside the chamber may differ from that actually happens out side in the field. Though emission data obtained using NFT-NSS chambers can be used for comparison of relative flux between treatments, many times these values are used to estimate mean N_2O emission rates from agricultural soils (Freibauer, 2003; Bouwman et al., 2002; Gregorich et al., 2005) and to develop default soil N_2O emission factors of the IPCC that are currently used in many countries to calculate GHG inventories. Therefore, biases in the accuracy of chamber N_2O data would also result in similar errors in soil N_2O emission inventories (Rochette, 2008). Rochette & Bertrand (2007) have summarized the improvements that were made over time to the NFT-NSS chamber methodology, they observed considerable variations with respect to chamber deployment time and number of air samples taken during deployment. Absence of a standard protocol may lead to biasness in flux estimate. Though these manually operated static chambers are inexpensive, and simple to operate, their coverage is limited over space and time. The covered area per measurement is usually less than 1m^2 and measurements are rarely taken more than once per day. There is report of presence of spots of enhanced N_2O emission from the field (Hellebrand et al., 2008) which is difficult to be taken account with the chamber method. Thus, this method is not well suited to describe daily variations or short-lived emission pulses induced by events such as rainfall, fertilization, re-wetting of dry soil and freeze-thaw. Therefore the uncertainty of annual flux estimates from manually operated chambers can be as high as 50% due to spatial and temporal variability (Flechard et al., 2007). In the absence of provision of air circulation inside the chamber head space, it has been shown that static chambers potentially underestimate fluxes (Pumpanen et al., 2004; Christiansen et al., 2011). Insulation of the chamber, provision of venting tube, power operated fan, use of air circulation pump, temperature correction, use of exetainers for storage of sample, maintenance of positive pressure during storage and handling of air samples and use of nonlinear model for determination of N_2O flux are some measures suggested to improve the reliability of emission data obtained through closed chamber method (Rochette, 2008).

Another approach of monitoring N_2O flux at field scale is use of micrometeorological techniques. This techniques use analyses of the atmospheric concentration of the gas and meteorological measurements such as wind speed, wet- and dry-bulb air temperatures, net radiation, and heat fluxes without disturbing the environmental conditions. The most widely used micrometeorological technique for N_2O flux measurements is the eddy covariance (EC) method, but the Relaxed Eddy Accumulation (REA) and the flux gradient method also have been applied to N_2O emission measurements (Skiba et al., 1996; Pattey et al., 2006; Desjardin et al., 2010). The area over which a flux can be integrated ranges from 0.01–1 km^2, depending on the height of the sampling tower. The limitation of this technology is that this is highly expensive and requires specialized instrumentation such as tuneable diode laser trace gas analyzers.

Strategies for reduction of nitrous oxide-nitrogen emission from rice field

There is direct linkage between nitrogen use efficiency and emissions of N_2O hence the strategies that increase the efficiency of N fertilizer use also reduce N_2O emissions (Aulakh et al. 1992; Monteny et al, 2006). These strategies include: forms of fertilizer (reduce anhydrous ammonia use), rate and method of application, matching N supply with demand, fertigation, applying fertiliser to the plant rather than the soil and the use of slow-release fertilizers, urease and nitrification inhibitors (Freney, 1997).

Matching N supply with crop demand

Application of nitrogen in splits in synchrony with the crop requirement is an important strategy to improve N use efficiency, minimization of N loss and regulation of N_2O emission from the rice field. Leaf color chart, SPAD meter, etc can be used to guide farmers in deciding the number of splits, amount of N applied per split, and the time of applications to match the N supply with real-time demand of rice crop. Site-specific nutrient management approach that includes site-specific quantitative knowledge of crop nutrient requirements, indigenous nutrient supply and the recovery efficiency of applied fertilizer nitrogen ensures about 30-40% increase in nitrogen use efficiency, has the potential of reducing N_2O-N emission from rice field. However these approaches needed to be standardized with respect to cultivars grown and agro climatic condition.

Use of controlled release fertilizers

The use of controlled release fertilizers, which are intended to supply nutrients to the soil solution and hence to the crop roots at a rate which more or less matches plant demand, has attracted considerable interest for many years, as a means of improving fertilizer use efficiency

(Cheng et al., 2002). Minami, (2005) reported that application of controlled-release fertilizers reduced the N_2O emissions. Minami (1994) compared N_2O losses from polyolefin-coated ammonium nitrate with uncoated ammonium sulfate and reported a 3 to 7-fold reduction in the emission of N_2O from arable soil.

Placement and source of fertilizer

Denitrification and N_2O losses of urea from flooded rice systems are further reduced when urea is deep placed as compared to surface broadcast application (Keerthisinghe et al., 1996; Liu et al., 2006). Application of N as anhydrous ammonia led to a much greater increase in emission of N_2O than the application of the same amount of fertilizer N as urea or aqueous ammonia (Breitenbeck & Bremner, 1986). Amendment of soil with NH_4^+ plus glucose resulted in an increased emission of N_2O, compared to treatment with either glucose or NH_4^+.

Use of nitrification inhibitors

Addition of nitrification inhibitors such as nitrapyrin, 2-chloro-6-(trichloromethyl)- pyidine (Pathak & Nedwell, 2001), dicyandiamide (Malla, 2005) and wax-coated calcium carbide (Keerthisinghe et al., 1996) to soil after fertilizer application significantly reduced fertiliser induced loss of nitrous oxide. Addition of dicyandiamide (DCD) to urea reduced total N_2O-N emission at all moisture regimes (Kumar et al., 2000). Vallejo et al. (2005) found that mixing pig slurry with DCD lowered N_2O emissions compared to slurry only.

Water management

In Irrigation systems, timing and frequency of irrigation also influence N_2O production. Negligible N_2O emission under continuous flooded conditions has been reported. In arid and semiarid areas, drip irrigation system reduced the N_2O emissions compared to the furrow irrigation (Rolston et al., 1982).

Tillage management

Tillage practices like no tillage or minimum tillage, bed planting, modifies N_2O emission through their impact on compaction, drainage, and aeration status of soil. However reports on effect of tillage on N_2O emission are highly inconsistent. Some studies showed an increase in N_2O emission with zero and no tillage systems (Aulakh et al., 1984; Ball et al., 1999). There is a need to monitor the N_2O emission under different tillage management in different rice production systems.

Conclusions

Rice and rice based production systems are one of the most intensively cultivated system. Because of excessive use of nitrogenous fertilizer and abysmal poor nitrogen use efficiency, this system is a major contributor of N_2O to the environment. However there are lots of variability in estimate of N_2O emissions from rice fields due to diverse soil and climate conditions and socio-economic status of the farmers. Besides that various crop management practices also influences the emission. Considerable research efforts are needed to improve the quantitative understanding of N dynamics in soil-plant-atmosphere system and reduce the ambiguities and inaccuracies associated with direct measurement of N_2O fluxes. Simulation models can be used for quantifying N_2O emissions under various agro-ecosystem but they need to be properly validated. Predictability of models is often not reliable due to difficulty in calibration of model in the absence of sufficient data. Considering the geographical spread and immense variability in environmental factor and management factor in rice production, ecosystem specific flux measurement is essential to reduce the uncertainties in national N_2O budget and improve the predictability of emission model.

In spite of volumes of research over past fifty years, not much progress has been made in improving nitrogen use efficiency of rice production system. Because of the lack of synchrony in nutrient supply and crop demand, recovery efficiency of applied N is low. Therefore, a strategy that ensures synchrony between N supply and demand, maximizes crop N uptake, minimizes N losses, and optimize indigenous soil N supply should be adopted to improve N use efficiency. Site specific nitrogen management and real time N management options have the potential to improve nitrogen use efficiency and reduce N_2O emission from rice field, but they need to be evaluated and standardized in different agro ecosystems.

References

Abao, E.B., Bronson, K.F., Wassmann R., & Singh, U. (2000). Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rainfed conditions. *Nutrient Cycling in Agroecosystems,* 58, 131-139.

Aulakh, M.S., & Bahl, G.S. (2001). Nutrient mining in agro climatic zones of Punjab. *Fertilizer News*, 46, 47-61.

Aulakh, M.S., Doran, J.W., & Mosier, A.R. (1992). Soil denitrification - significance, measurement, and effects of management. *Advances in Soil Sciences*, 18, 2-42.

Aulakh, M.S., Rennie, D.A., & Paul, E.A. (1984). Acetylene and N-serve effects upon N_2O emissions from NH_4^+ and NO_3^- treated soils under aerobic and anaerobic conditions. *Soil Biology and Biochemistry*, 16, 351-356.

Ball, B.C., Scott, A., & Parker, J.P. (1999). Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. *Soil and Tillage Research,* 53, 29-39.

Baruah, B., Gogoi, P., & Gupta, P.K. (2010). N_2O emission in relation to plant and soil properties and yield of rice varieties. *Agronomy of Sustainable Development,* 30, 733-742.

Bouwman, A.F., Boumans, L.J.M., & Batjes, N.H. (2002). Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*, 16(4), 6.1-6.13.

Breitenbeck, G.A., & Bremner, J.M. (1986). Effects of rate and depth of fertilizer application on emission of nitrous oxide form soil fertilized with anhydrous ammonia. *Biology and Fertility of Soils,* 2, 201-204.

Bronson, K.F., Neue, H.U., Singh, U., & Abao, E.B.Jr. (1997a). Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: I. Residue, nitrogen and water management. *Soil Science Society of America Journal,* 61, 981-987.

Bronson, K.F., Neue, H.U., Singh, U., & Abao, E.B. Jr. (1997b). Automated chamber measurements of methane and nitrous oxide flux in a flooded rice soil: II. Fallow period emissions. *Soil Science Society of America Journal,* 61, 988-993.

Buresh, R.J., & De Datta, S.K. (1990). Denitrification losses from puddled rice soils in the tropics. *Biology and Fertility of Soils,* 9, 1-13.

Cai, Z., Xing, G., Yan, X., Xu, H., Tsuruta, H., Yagi, K., & Minami, K. (1997). Methane and nitrous oxide emissions from rice paddy fields as affected by nitrogen fertilizers and water management. *Plant and Soil,* 196, 7-14.

Cao, J., Ren, L., Yang, B., Xu, H., & Xing, G. (1999). Characteristics of N_2O emission from rice fields in the hilly area of southern Jiangsu province. *Chinese Journal of Ecology*, 18, 6-9.

Chalk, P.M., & Smith, C.J. (1983). In J.R. Freney, Simpson, J. Reds (Eds.), *Gaseous loss of nitrogen from plant-soil systems*. pp. 65-89.

Chen G.X., Huang G.H., Huang B., Yu K.W., Wu J., & Xu, H. (1997). Nitrous oxide and methane emissions from soil plant systems. *Nutrient Cycling in Agroecosystems,* 49, 41-45.

Cheng, W., Nakajima, Y., Sudo, S., Akiyama, H., & Tsuruta, H. (2002). N_2O and NO emissions from Chinese cabbage field as influenced by band application of urea or controlled-release urea fertilizers. *Nutrient Cycling in Agroecosystems,* 63, 231-238.

Christiansen, J.R., Korhonen, J.F.J., Juszczak, R., Giebels, M., & Pihlatie, M. (2011). Assessing the effects of chamber placement, manual sampling and headspace mixing on CH_4 fluxes in a laboratory experiment. *Plant and Soil,* 343(1-2), 171-185.

Davidson, E.A., Keller, M., Erickson, H.E., Verchot, L.V., & Veldkamp, E. (2000). Testing a conceptual model of soil emissions of nitrous and nitric oxides. *Bio Science,* 50, 667-680.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Da Silva Dias, P.L., Wofsy, S.C., & Zhang, X. (2007). Coupling between changes in the climate system and biogeochemistry. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, B.R. Miller (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* (pp.500-587). Cambridge, UK and New York, US: Cambridge University Press.

Desjardins, R.L., Pattey, E., Smith, W.N., Worth, D., Grant, B., Srinivasan, R., MacPherson, J.I., & Mauder, M. (2010). Multiscale estimates of N_2O emissions from agricultural lands. *Agricultural and Forest Meteorology,* 150, 817-824.

Dobbie K.E., McTaggart, I.P., & Smith, K.A. (1999). Nitrous oxide emissions from intensive agricultural systems: Variations between crops and seasons, key driving variables, and mean emission factors. *Journal of Geophysical Research,* 104, 2681-2689.

Fillery, I.R.P., & Vlek, P.L.G. (1982). The significance of denitrification of applied nitrogen in fallow and cropped rice soils under different flooding regimes. I. Greenhouse experiments. *Plant Soil,* 65, 153-169.

Firestone, M. (1982). Biological denitrification. In F.J. Stevenson *et al.* (Eds.), *Nitrogen in agricultural soils.* (pp.289-326). Madison, WI, USA: Soil Science Society of America.

Firestone, M.K., and Davidson, E.A. (1989). Microbiological basis of NO and N_2O production and consumption in soil. *In* M.O. Andreae, K.S. Schimel (Eds.), *Exchange of trace gases between terrestrial ecosystems and the atmosphere*. New York: John Wiley & Sons Ltd.

Flechard, C.R., Ambus, P., Skiba, U., Rees, R.M., Hensen, A., van Amstel, A., van den Pol-van Dasselaar, A., Soussana, J.F., Jones, M., Clifton-Brown, J., Raschi, A., Horvath, L., Neftel, A., Jocher, M., Ammann, C., Leifeld, J., Fuhrer, J., Calanca, P., Thalman, E., Pilegaard, K., Di Marco, C., Campbell, C., Nemitz, E., Hargreaves, K.J., Levy, P.E., Ball, B.C., Jones, S.K., van de Bulk, W.C.M., Groot, T., Blom, M., Domingues, R., Kasper, G., Allard, V., Ceschia, E., Cellier, P., Laville, P., Henault, C., Bizouard, F., Abdalla, M., Williams, M., Baronti, S., Berretti, F., & Grosz, B. (2007). Effects of climate and management intensity on nitrous oxide emissions in grassland systems across Europe. *Agriculture, Ecosystems & Environment,* 121, 135-152.

Freibauer, A. (2003). Regionalised inventory of biogenic greenhouse gas emissions from European agriculture. *European Journal of Agronomy,* 19, 135-160.

Freney, J.R. (1997). Emission of nitrous oxide from soils used for agriculture. *Nutrient Cycling in Agroecosystems,* 49, 1-6.

Ghosh S., Majumdar, D., & Jain, M.C. (2003). Methane and nitrous oxide emissions from an irrigated rice of North India. *Chemosphere,* 51, 181-195.

Gregorich, E.G., Rochette, P., VandenBygaart, A.J., & Angers, D.A. (2005). Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Research,* 83, 53-72.

Haynes, R.J. (1986). In R.J. Haynes (Ed.), *Mineral nitrogen in the plant-soil system*. (pp. 127-165). New York: Academic Press.

Hellebrand, H.J.V., & Scholz, J. (2008). Kern Nitrogen conversion and nitrous oxide hot spots in energy crop cultivation. *Research in Agricultural Engineering,* 54(2), 58-67.

Inubushi, K., Barahona, M A., & Wassman, R. (1999). Effects of salts and moisture content on N_2O emission and nitrogen dynamics in yellow soil and *andisol* in model experiments. *Biology and Fertility of Soils,* 29, 401-407.

IPCC. (2006). In S. Eggleston, L. Buendia, K. Miwa, T. Ngara, K. Tanabe (Eds.), *IPCC Guidelines for National Greenhouse Gas Inventories*. Japan: Institute for Global Environmental Strategies, Hayama on behalf of IPCC, National Greenhouse Gas Inventory Program.

IPCC. (2007). In M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (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, UK and New York, USA: Cambridge University Press.

Keerthisinghe, D.G., Jian, L.X., Qixiang, L., Mosier, A.R., Lin, X.J., & Luo, Q.X. (1996). Effect of encapsulated calcium carbide and urea application methods on denitrification and nitrogen loss from flooded rice. *Fertilizer Research,* 45(1), 31-36.

Kroeze, C., Mosier, A.R., & Bouwman, A.F. (1999). Closing the global N_2O budget: A retrospective analysis 1500–1994. *Global Biogeochemical Cycles,* 13, 1-8.

Kumar, U., Jain, M.C., Pathak, H., Kumar, S., & Majumdar, D. (2000). Effects of moisture levels and nitrification inhibitors on N_2O emission from a fertilized alluvial clay loam soil. *Current Science,* 79 (2), 224-228.

Liu, X.J., Mosier, A.R., Halvorson, A.D., & Zhang, F.S. (2006). The impact of nitrogen placement and tillage on NO, N_2O, CH_4 and CO_2 fluxes from a clay loam soil. *Plant Soil,* 280, 177-188.

Majumdar, D., Kumar, S., Patahk, H., Jain, M.C., & Kumar, U. (2000). Reducing nitrous oxide emission from an irrigated paddy in North India with nitrification inhibitors. *Agriculture, Ecosystems & Environment,* 81(3), 163-169.

Malla, G. (2005). Mitigating nitrous oxide and methane emission from soil in rice-wheat system of the Indo-Gangetic Plain with nitrification and urease inhibitors. *Chemosphere,* 58, 141-147.

Menyailo, O.V., Stepanov, A.L., & Umarov, M.M. (1997). The transformation of nitrous oxide by denitrifying bacteria in Solonchaks. *Pochvovedenie,* 213-215.

Minami, K. (1994). In K. Minami et al. (Eds.), *CH_4 and N_2O global emissions and controls from rice field and their agricultural and industrial sources*. Yokendo, Tokyo: NIAES.

Minami, K. (2005). N cycle, N flow trends in Japan, and strategies for reducing N_2O emission and NO_3^{-} pollution. *Pedosphere,* 15(2), 164-172.

Monteny, G.J., Bannink, A., & Chadwick, D. (2006). Greenhouse gas abatement strategies for animal husbandry. *Agriculture, Ecosystems & Environment,* 112,163-170.

Mosier, A.R., & Kroeze, C. (1998). A new approach to estimate emissions of nitrous oxide from agriculture and its implications for the global N_2O budget. *Global Change Newsletter,* 34, 8-13.

Mosier, A.R. (1994). Nitrous oxide emissions from agricultural soil. *Fertilizer Research,* 37, 191-200.

Murakami, T., Owa, N., & Kumazawa, K. (1987). The effect of soil conditions and nitrogen form on N_2O evolution by denitrification. *Soil Science and Plant Nutrition,* 33(1), 35-42.

Naqvi, S.W.A., & Noronha, R.J. (1991). Nitrous oxide in the Arabian Sea. *Deep Sea Research*, 38, 871-890.

Pathak, H, & Nedwell, D.B. (2001). Strategies to reduce nitrous oxide emission from soil with fertilizer selection and nitrification inhibitor. *Water Air and Soil Pollution,* 129, 217-228.

Pathak, H., Li, C., & Wassmann, R. (2005). Greenhouse gas emissions from Indian rice fields: Calibration and upscaling using the DNDC model. *Biogeosciences*, 2, 113-123.

Pattey, E., Strachan, I., Desjardins, R., Edwards, G., Dow, D., & Macpherson, J. (2006). Application of a tunable diode laser to the measurement of CH_4 and N_2O fluxes from field to landscape scale using several micrometeorological techniques. *Agricultural and Forest Meteorology,* 136, 222-236.

Pumpanen, J., Kolari, P., Ilvesniemi, H., Minkkinen, K., Vesala, T., Niinist¨o, S., Lohila, A., Larmola, T., Morero, M., Pihlatie, M., Janssens, I., Yuste, J.C., Gr¨unzweig, J. M., Reth, S., Subke, J., Savage, K., Kutsch, W., Østreng, G., Zieglerm, W., Anthonim P., Lindroth A., & Hari, P. (2004). Comparison of different chamber techniques for measuring soil CO_2 efflux. *Agricultural and Forest Meteorology,* 123, 159-176.

Ritchie, G.A.F., & Nicholas, D.J.D. (1972). Identification of the sources of nitrous oxide produced by oxidative and reductive processes in *Nitrosomonas europaea*. *Biochemical Journal*, 126, 181-191.

Rochette, P., & Eriksen-Hamel, N.S. (2008). Chamber measurements of soil nitrous oxide flux: Are absolute values reliable?. *Soil Science Society of America Journal,* 72, 331-342.

Rochette, P., & Bertrand, N. (2007). Soil-surface gas emissions. In M. Carter, E.G. Gregorich (Eds.), *Soil sampling and methods of analysis* (2nd ed.). Boca Raton, FL: CRC Press.

Rolston, D.E., Sharpley, A.N.D., Toy, W., & Broadbent, F.E. (1982). Field measurement of denitrification: III. Rates during irrigation cycles. *Soil Science Society of America Journal,* 46, 289-296.

Skiba, U., Hargreaves, K.J., Beverland, I.J., O'Neill, D.H., Fowler, D., & Moncrieff, J.B. (1996). Measurement of field scale N_2O emission fluxes from a wheat crop using micrometeorological techniques. *Plant Soil,* 181, 139-144.

Syakila, A. & Kroeze, C. (2011). The global nitrous oxide budget revisited. *Greenhouse Gas Measurement & Management,* 1, 17-26.

Tsuruta, H., Kanda, K., & Hirose, T. (1997). Nitrous oxide emission from a rice paddy field in Japan. *Nutrient Cycling in Agroecosystems,* 49, 51-58.

Vallejo, A., García-Torres, L., Diez, J.A., Arce, A., & Lopez-Fernandez, S. (2005). Comparison of N losses (NO_3^-, N_2O, NO) from surface applied, injected or amended (DCD) pig slurry, of an irrigated soil in a Mediterranean climate. *Plant Soil,* 272, 313-325.

Wang, W.J., & Rees, R.M. (1996). In O. Van Cleemput, G. Hofman, (Eds.), *Progress in nitrogen cycling studies:* Proceedings of the 8th Nitrogen Workshop. (pp. 659-662). The Netherlands: Kluwer Academic Publishers.

Xuri, X., Wang, M., & Wang, Y. (2003). Using a modified DNDC model to estimate N_2O fluxes from semi-arid grassland in China. *Soil Biology and Biochemistry,* 35, 615-620.

Yue, J., Yi Shi, Wei Liang, Jie Wu, Chenrui Wang, & Guohong Huang. (2005). Methane and nitrous oxide emissions from rice field and related microorganism in black soil, northeastern China. *Nutrient Cycling in Agroecosystems*, 73, 293-301.

ZouJ, Yao Huang, Jingyan Jiang, Xunhua Zheng & Ronald L. Sass. (2005). A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application. *Global Biogeochemical Cycles,* 19, 1-9.

*****

Chapter 5

Soil organic carbon sequestration in rice based cropping system in Indo-Gangetic Plains

A.K. Nayak*, R. Raja, Anjani Kumar, Mohammad Shahid, Rahul Tripathi, Sangita Mohanty, P. Bhattacharyya and B.B. Panda
Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: aknayak20@yahoo.com

The soil organic carbon (SOC) concentration of most soils in India is low because of the low clay contents in alluvial soils of the Indo-Gangetic plains (IGP), coarse-textured soils of southern India, and arid zone soils of north-western India (Dhir et al., 1991). These soils have been cultivated for centuries, and often with low off-farm input, based on systems that involve removal of crop residue and dung for fuel and other purposes. The prevalent low levels of SOC concentrations are also attributed to soil-mining practices of excessive tillage, imbalance in fertilizer use, little or no crop residue returned to the soil, and soil degradation (Lal, 2004). Hence in India, the importance of organic matter addition was considered so important that numerous studies with organic manures were conducted in seventies. The primary purpose was to determine their nutrient equivalence in comparison to chemical fertilizers. Despite the fact that organic manures contain almost all the essential plant nutrients and produce other non-nutrient benefits also, their value was principally assessed in terms of nitrogen (N) only (Katyal, 1993; Tandon, 1997). In long term experiments, the symptoms of 'fatigue', witnessed by stagnating or declining yields in intensive rice-based systems of IGP (Ram, 1998; Dawe et al., 2000; Duxbury et al., 2000; Ladha et al., 2003) is often attributed to decline in soil organic matter (SOM) quality and quantity (Dawe et al., 2000; Yadav et al., 2000; Ladha et al., 2003). Long term studies have shown that practices like improved fertilizer management, manuring and compost application, residue incorporation, crop rotation, green manuring, reduced tillage, adjusting irrigation method and restoration of waste land enhanced soil carbon build up and storage (Kimble et al., 2002). These practices not only promote sustainable agriculture but also mitigate the impact of climate change through both carbon sequestration and minimized emissions of greenhouse gases (GHGs). A single land use or management practice will not be effective at sequestering carbon (C) in all regions (Lal et al., 1998). The cropping systems and the management practices that could provide C input higher than the above critical level are likely to sustain the SOC level and maintain good soil health in the subtropical regions of the Indian subcontinent (Mandal et al., 2007). In recent years, extensive attention has been paid to the sustainability and the effects of crop management practices on soil organic carbon dynamics and its sequestration in rice-wheat systems of IGP which is one of the largest production systems in the world.

Indo-Gangetic Plains

The name *Indo-Gangetic Plains* (IGP) is derived from the two river systems in the region *Indus* and *Ganges*. The IGP of India extends from 21°45′ to 31°0′ N latitude and from 74°15′ to 91°30′ E longitude and in India includes mostly the states of Punjab, Haryana, Delhi, Uttar Pradesh, Bihar, West Bengal and the northern parts of Rajasthan and Tripura, covering a total area of 43.7 m ha, i.e. 13% of the total area of the country. The IGP in India is relatively homogenous in

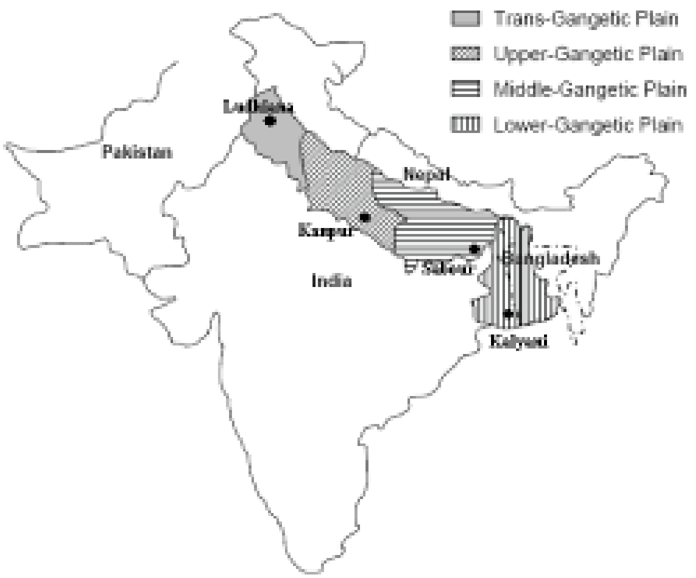


FIGURE 1. *Map of India (not to the scale) showing the Indo-Gangetic Plains*

vegetation but can be subdivided into four broad transects-the Trans (in the Indian Punjab and Haryana), Upper- (in the Western UP) Middle- (in the Eastern UP and Bihar), and Lower (in eastern India, West Bengal) Indo-Gangetic Plains (Fig. 1)

Climate in the IGP is dominated by the summer monsoon but varies strongly, going from west to east. The mean annual rainfall varies from 500-800 mm in the north-western part to as high as 1500-3200 mm in the east. Mean annual temperature in the IGP varies from 22 to 27°C. Summer temperatures are generally higher in the north-western part, reaching daytime temperatures as high as 45°C in June-July, whereas in winter temperatures may be as low as 4°C. In the eastern parts of the IGP, maximum temperatures in summer reach 38°C and minimum temperatures in winter may be as low as 10°C (White & Rodriguez-Aguilar, 2001).

Rice-wheat cropping system

Rice-wheat occupies about 7.15 m ha (66%) of the total area of 10.81 m ha of rice-based cropping in the IGP (Yadav & Subba Rao, 2001). The largest area of the rice-wheat rotation is found in Trans Gangetic Plains (TGP), followed by Middle Gangetic Plains (MGP) and Upper Gangetic Plains (UGP), while it occupies a small area in Lower Gangetic Plains (LGP) (0.23 Mha), mostly including other crops, such as summer rice, jute, gram and vegetables in the rice-wheat sequence. The rice–wheat (RW) system of IGP is of immense importance for the food security and livelihoods in India.

The two major cereals in the RW rotation have contrasting edaphic requirements. For rice, soil is puddled (wet tillage) and kept under continuous submergence. In contrast, wheat is grown in upland well-drained soil having good tilth. Puddling and transplanting are highly labor, water, time and energy intensive. The RW rotation creates alternate aerobic and anaerobic environment.

Salinity and sodicity affect a large area of IGP, in excess of 5.5 m ha; of which significant proportion of the land is utilized for agricultural production, including rice-wheat cropping. Compared to non-saline and non-sodic soil, SOC levels in these soils are lower, due primarily to reduced biomass production, hence reduced organic C input, but also to enhanced or similar organic C decomposition rates, the later is accentuated or maintained by increased dispersion of aggregates due to sodicity and hence exposure to protected organic C within aggregates, and its resolution and availability to the bacterial-dominated microbial population. Furthermore, as this source of SOC is depleted, even microbial biomass carbon (MBC) is utilized, which further reduces microbial biomass. Also, the dissolved organic C is subjected to leaching and run off losses (Wong et al., 2010)

Soil organic carbon dynamics under rice-wheat system

In IGP rice in wet season and wheat in dry season are cultivated in sequence, providing an alternate anaerobic and aerobic conditions round the year. Carbon mineralization was found to be three times slower under anaerobic than under aerobic conditions (DeBusk & Reddy, 1998). This slower decomposition rate, because of slower lignin degradation and the associated enrichment of young humus with phenolic compounds released from rice stubble decomposition, partially explains the relatively stronger accumulation of organic matter in wetland soils typical to rice soils in kharif. With an increasing number of annual irrigated rice crops, the phenolic nature of the humic acid fraction in soil increases (Olk et al., 1996). Microbial dynamics play a key role in C and N dynamics, as microbes are the active agents in soil organic natter (SOM) decomposition. Microbial biomass fluctuates under the influence of varying environmental conditions and substrate availability. Under aerobic conditions, aerobic microorganisms, especially fungi, dominate the soil microbial biomass and release phenols from decomposing lignin. Anaerobic microorganisms also decompose aromatic compounds such as phenols, but use different pathways (Evans, 1977). The phenolic structures liberated from parent lignin molecules often have a longer residence time in anaerobic soil than in aerobic soil and thus have more chance of polymerizing with some other component of SOM; consequently, SOM formed under submerged conditions undergoes stronger polymerization. Rice residues having higher C: N ratio decompose at slower rate than the wheat residues.

Soil organic carbon sequestration under rice-wheat system

An emerging concern in RW systems is the reduction in SOC-content and the associated reduced nutrient supplying capacity. Nambiar (1995) reported that SOC in treatments not receiving farmyard manure (FYM) declined in some long-term experiments (LTEs) in India, and that applications of FYM before either crop were effective in building up SOC and boosting crop yields. In the present rice-based cropping systems, crop residues are either burnt or removed from the field for stock feed and bedding, roofing and fencing. In India each year 19.6 million tonnes of straw of rice and wheat are burnt if used as recycled biomass, this potentially translates into 3.85 m t of organic carbon, 59,000 tonnes of nitrogen, and 2,000 tonnes of phosphorous and 34,000 tonnes of potassium and could be one of the potential options for improving the SOC stocks of soil. When residues are incorporated into the soil, mineral nitrogen is immobilized during decomposition, which may reduce nitrogen uptake and yield of the succeeding wheat crop by about 40% (Sidhu & Beri, 1989), whereas the combined use of rice or wheat straw and inorganic fertilizer in RW systems can increase the yield of rice and wheat (Mahapatra et al., 1991) and build up SOC.

Across the different agro-climatic zones of IGP, comparatively higher SOC content was observed in LGP followed by MGP, UGP and TGP, respectively. The higher SOC content in LGP and MGP over TGP and UGP is due to higher clay content in the soil, low land situation, reduced conditions due to incomplete drainage and humid climate (Nayak et al., 2012). Organic matter decomposition proceeds faster in sandy than in clayey soils (Katyal, 2001), while the rate of soil organic matter decomposition is lessened in lowland rice fields, apparently due to excessively reduced conditions (Watanabe, 1984). Because of the lack of oxygen under submerged conditions, even a modest oxygen demand for microbial activity can not be met if large pores are filled with water, resulting in a decreased rate of decomposition (Jenkinson, 1988). Therefore, there is an incomplete decomposition of organic materials and decreased humification of organic matter under submerged conditions, resulting in net accumulation of organic matter in soils (Sahrawat, 2004).

Continuous application of NPK for 23–26 year in RW system has resulted in significantly higher SOC over control in 0–15 cm soil depth across different agro-climatic zones of IGP. Intensive RW system in IGP without application of fertilizers (control) resulted in reduction (22 and

35% decrease) of SOC concentration over initial value in middle and lower IGP, respectively whereas at trans and upper IGP, it has more or less maintained the SOC level (Nayak et al., 2012). As initial SOC concentration was comparatively higher at middle and lower IGP than trans- and upper- IGP, it would be hard to maintain SOC contents without fertilization and/or organic matter addition in middle and lower IGP. However, because of very low initial value, the SOC concentration in the control plot was maintained at trans- and upper- IGP despite declining yield trend. Application of recommended dose of N–P–K resulted in increased SOC in surface soil over the initial level at all places except at LGP where a slight reduction was recorded. The higher stubble and root biomass retention commensurating with higher yield in the N–P–K fertilized plot might have improved the SOC in surface soil at all sites except at LGP where initial SOC value was comparatively higher than others. However, compared to unmanured/unfertilized control, the fields receiving recommended N–P–K fertilizer resulted higher SOC concentration in surface soil at all the places. Results of other long-term experiments have also shown that with optimum application of inorganic fertilizers, the SOC content has either been increased (Purakayastha et al., 2008a; Zhang et al., 2009) or maintained over the years (Biswas & Benbi, 1997). Substitution of 50% N through FYM or crop residue (CR) or green manure (GM) to rice has improved SOC significantly over NPK treated plots at all the locations. The addition of FYM, CR, and GM complemented with N–P–K increased the organic carbon content of soil over that achieved with N–P–K alone, due to additive effect of N–P–K and organics and interaction between them (Nayak et al., 2012). A similar build up of SOC due to cropping with the application of chemical fertilizer combined with manure (Rudrappa et al., 2006), paddy straw (Verma & Bhagat, 1992), and green manure (Yadav et al., 2000) were also reported from long-term experiments. Bharambe & Tomar (2004) reported an increase in organic carbon content in a RW system when inorganic fertilizers were applied along with FYM. Many long-term experiments have shown that both chemical fertilizer and manure application increased the SOC content in the soil, but the increases in SOC were much higher with organic manure (Christensen, 1996; Smith et al., 1997; Aoyama & Kumakura, 2001)

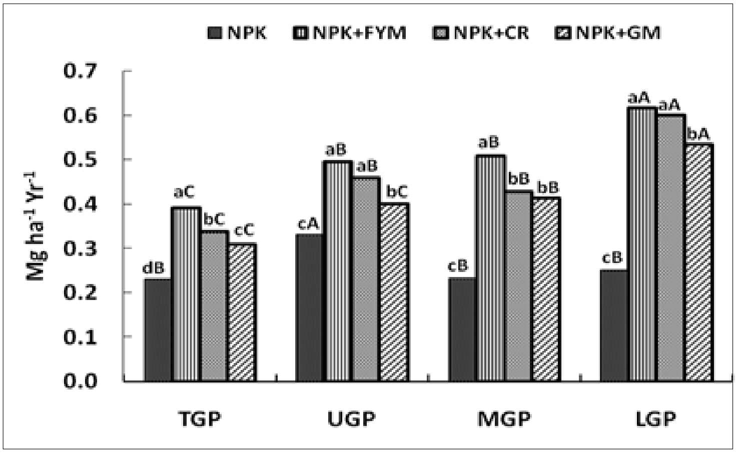


FIGURE 2. *Changes in soil organic carbon pool (Mg ha^{-1} Yr^{-1}) in different integrated nutrient management system over the control under different agro-climatic situation in Indo-Gangetic Plains. (Means with the same lower case letters are not significantly different in different treatments at same centre; means with the same uppercase letters are not significantly different in a treatment at different centres). Adapted from Nayak et al. (2012)*

Using the mass of SOC in the control treatment as reference point and number of years of interventions, Nayak et al. (2012) estimated the sequestration rate (rate of net SOC increase), which varied from 0.231 to 0.332 t ha^{-1}yr^{-1} in N–P–K treated plot under continuous RW cropping system in the different agro-climatic zones of IGP (Fig. 2). Among the treatments, NPK + FYM recorded significantly higher sequestration rate over all other treatments across all the agro-climatic zones except at LGP and UGP where the sequestration rate between NPK + FYM and NPK + CR were at par. Their study indicates that applications of N–P–K fertilizer with or without organics can sequester carbon in soils at all the sites of IGP. Response of SOC to carbon input has been controversial (Campbell et al., 2007; Purakayastha et al., 2008b). Hao et al. (2008) reported that combined applications of inorganic fertilizers (N–P and N–P–K fertilization) with or without manure can sequester carbon in soils at most of the sites of northern China. The soil carbon sequestration rates as reported by Nayak et al. (2012) vary from 0.08 to 0.98 t ha^{-1} yr^{-1} in IGP under the NPK, NPK + FYM, NPK + CR and NPK + GM treatments, which are comparable to those from other studies (Akselsson et al., 2005; Causarano et al., 2008; Kundu et al., 2007; Hien et al., 2006; Kroodsma & Field, 2006). The soil carbon sequestration with response to application of fertilizer complemented with organics was higher in LGP and MGP in humid climate than in TGP and UGP lying in semiarid climate. While budgeting C stocks in different eco-regions of Asia, Bronson et al. (1998) indicated a possible conservation or even increase in C stock in soil in the lowland tropics, despite high temperature prevalent throughout the years, which favours rapid mineralization of C. They opined that this was due to the relatively slow rate of soil C mineralization under anaerobiosis and also the large C inputs from nonvascular plants (photosynthetic algal communities) in the soil–flood water ecosystem. Soils rich in clay may have more potential to sequester carbon than those rich in sand and silt in the similar climate zone, due to the physical protection of mineral on SOC (Matus et al., 2008) which also partly explained the higher SOC sequestration rate at LGP having higher clay percent.

Soil organic carbon sequestration under salt affected soil

Saline and sodic soils are of widespread occurrence in the arid and semiarid regions of northern India, limiting the productivity of more than 2.5 m ha of otherwise arable lands in the IGP (Abrol & Bhumbla, 1971). Afforestation and reclaimation through agroforestry systems have been reported to increase soil organic matter content and improve the biological properties of sodic soils (Singh, 1996; Singh & Singh, 1997). Phytoremediation of sodic soil of IGP soil can sequester 0.826 Mg C ha^{-1} yr^{-1} under *Prosopis juliflora* plantations while intensive cropping of RW, including the application of gypsum amendments and optimum nutrient management, can sequester 0.689 Mg C ha^{-1} yr^{-1} (A.K. Nayak personal communication, 18 Feb, 2012). Kaur et al. (2002) suggested that various land –use system can sequester organic C in the range of 0.2 to 0.8 Mg C ha^{-1} per year. In long term experiment on a sodic soil, the changes in organic C under four tree species revealed that *Prosopis juliflora* is the most efficient species in terms of increasing SOC accumulation. However, the efficacy of application of amendments especially plant materials in enhancing SOC status and amelioration of these soils depends on the plant species and their ability to grow and produce biomass (Qadir et al., 2002). In general, it has been found that the amelioration of sodic and saline soils through the use of plants in the form of vegetation and crop residues is a slow process and this process can be enhanced by the application of amendments such as gypsum to reclaim the sodic soils followed by phytoremediation by cultivating RW. However, phytoremediation is advantageous that in addition to supplying organic matter, it provides source of plant nutrients, which are released during their mineralization in the soil. Moreover, plant roots produce root exudates and mucilages, resulting in increased microbial activity and microbial products in and around rhizosphere for aggregate formation and stabilization. Growing roots also provide channels for enhanced infiltration and hydraulic conductivity for rapid leaching of excess salts.

Remediation of even 10% area of salt- affected lands, achieving an estimated SOC sequestration of 0.2 Mg C ha^{-1} yr^{-1} over a 50-year period (approximately 50% of the potential C sequestration rate), may lead to 0.8 Pg C sequestered in SOC in these soils. Therefore, the potential for salt-affected soils to sequester SOC is large and significant. It is expected that large proportion of C sequestration will occur or result in the formation and stabilization of soil aggregates such as SOM-Ca^{2+}- clay aggregates, and as protected SOC against rapid microbial decomposition. However, research is required to validate this SOC sequestration mechanism after restoration of salt-affected soils, since, besides SOC benefits other benefits occur in improved physical and chemical characteristics of the soil.

Conclusions

There is a need for more quantitative assessment of the carbon sequestration potential of agricultural soils of IGP under different management practices for different soil types, climates and agricultural systems by supporting existing long term cropping system trial sites and by establishment of new ones where appropriate; quantifying interactions of SOC sequestration with emissions of GHGs and developing soil carbon models that can account for locally relevant agricultural management practices. There is also a need for assessment of how rehabilitation processes affect C cycling and C stocks, and how to maximise the accumulation of C stocks in the salt affected areas of IGP where SOC stocks are very small.

References

Abrol, I.P., & Bhumbla, D.R. (1971). Saline and alkaline soils in India, their occurrence and management. *World Soil Resources, FAO Report*, 41, 42-51.

Akselsson, C., Berg, B., Meentemeyer, V., & Westling, O. (2005). Carbon sequestration rates in organic layers of boreal and temperate forest soils - Sweden as a case study. *Global Ecology and Biogeography,* 14, 77-84.

Aoyama, M., & Kumakura, N. (2001). Quantitative and qualitative changes of organic matter in an ando soil induced by mineral fertilizer and cattle manure application for 20 years. *Soil Science and Plant Nutrition,* 47, 241-252.

Bharambe, A.P., & Tomar, A. (2004). Direct and residual effect of FYM and inorganic nutrients on rice–wheat cropping system in *vertisol*. *PKV Research Journal,* 28, 47-52.

Biswas, C.R., & Benbi, D.K. (1997). Sustainable yield trends of irrigated maize and wheat in a long-term experiment on loamy sand in semi-arid India. *Nutrient Cycling in Agroecosystems,* 46, 225-234.

Bronson, K.F., Cassman, K.G., Wassmann, R., Olk, D.C., Noordwijk, M., & Van Garrity, D.P. (1998). Soil carbon dynamics in different cropping systems in principal eco-regions of Asia. In: R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (Eds.), *Management of carbon sequestration in soil*. (pp. 35-57). Boca Raton, NY: CRC Press.

Campbell, C.A., Vanden Bygaart, A.J., Grant, B.B., Zentner, R.P., McConkey, B.G., Lemke, R.L., Gregorich, E.G., & Fernandez, M.R. (2007). Quantifying carbon sequestration in a conventionally tilled crop rotation study in southwestern Saskatchewan. *Canadian Journal of Soil Science,* 87, 23-38.

Causarano, H.J., Doraiswarny, P.C., McCarty, G.W., Hatfield, J.L., Milak, S., & Stern, A.J. (2008). EPIC modeling of soil organic carbon sequestration in croplands of Lowa. *Journal of Environmental Quality,* 37, 1345-1353.

Christensen, B.T. (1996). The Askov long-term experiments on animal manure and mineral fertilizers. In D.S. Powlson, P. Smith, J.U. Smith (Eds.), *Evaluation of soil organic matter: Models using existing datasets*. (Vol. 138). (pp. 301-312). NATO, ASI: Springer, Heidelberg.

Dawe, D., Dobermann, A., Moya, P., Abdulrachman, S., Singh, B., Lal, P., Li, S.Y., Lin, B., Panaullah, G., Sariam, O., Singh, Y., Swarup, A., Tan, P.S., & Zhen, Q.X. (2000). How widespread are yield declines in long-term rice experiments in Asia?. *Field Crops Research,* 66, 175-193.

DeBusk, W.F., & Reddy, K.R. (1998). Turnover of detrital organic carbon in a nutrient impacted Everglades marsh. *Soil Science Society of America Journal*, 62, 1460-1468.

Dhir, R.P., Chaudhary, M.R., Nath, J., & Somani, L.L. (1991). Constraints of sandy soils of arid and adjoining areas of western and northern India and their management. In T.D. Biswas (Ed.), *Soil-related constraints in crop production*. Indian Soc. Soil Sci. Bull. Vol. 15. (pp. 52-69). New Delhi, India.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., & Bronson, K.F. (2000). Analysis of long-term soil fertility experiments with rice–wheat rotations in South Asia. In *Long-term soil fertility experiments with rice–wheat rotations in South Asia.* Rice–Wheat Consortium Pap. Ser. No. 6. (pp. 7-22). New Delhi: Rice–Wheat Consortium for the Indo-Gangetic Plains.

Evans, W.C. (1977). Biochemistry of the bacterial catabolism of aromatic compounds in anaerobic environments. *Nature* (London), 270, 17-22.

Hao, X.H., Liu, S.L., Wu, J.S., Hu, R.G., Tong, C.L., & Su, Y.Y. (2008). Effect of long-term application of inorganic fertilizer and organic amendments on soil organic matter and microbial biomass in three subtropical paddy soils. *Nutrient Cycling in Agroecosystems,* 81, 17-24.

Hien, E., Ganry, F., & Oliver, R. (2006). Carbon sequestration in a savannah soil in southwestern Burkina as affected by cropping and cultural practices. *Arid Land Research and Management,* 20, 133-146.

Jenkinson, D.S. (1988). Soil organic matter and its dynamics. In A. Wild (Ed.), *Russell's soil conditions and plant growth* (11th ed.). (pp. 564-607). Longman Group UK Limited.

Katyal, J.C. (1993). Integrated nutrient management and supply: An overview. *Proceedings of Indian National Science Academy,* 59, 161-172.

Katyal, V.V. (2001). Conservation of organic carbon in relation to crop productivity, yield stability and soil fertility under rice (*Oryza sativa*)–wheat (*Triticum aestivum*) cropping system. *Indian Journal of Agronomy,* 46, 1-4.

Kaur, B., Gupta, S.R., & Singh, G. (2002). Bioamelioration of a sodic soil by silvopastoral systems in northwestern India. *Agroforestry Systems,* 54, 13-20.

Kimble, J.M., Lal, R., & Follett, R.R. (2002). Agricultural practices and policy options for carbon sequestration: What we know and where we need to go?. In J.M. Kimbel, R. Lal, R.F. Follett (Eds.), *Agricultural practices and policies for carbon sequestration in soil.* (pp. 512). New York: Lewis.

Kroodsma, D.A., & Field, C.B. (2006). Carbon sequestration in California agriculture, 1980-2000. *Ecological Applications,* 16, 1975-1985.

Kundu, S., Bhattacharyya, R., Prakash, V., Ghosh, B.N., & Gupta, H.S. (2007). Carbon sequestration and relationship between carbon addition and storage under rainfed soybean wheat rotation in a sandy loam soil of the Indian Himalayas. *Soil and Tillage Research,* 92, 87-95.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Singh, B., Singh, Y., Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., & Hobbs, P.R. (2003). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research,* 81, 159-180.

Lal, R. (2004). Soil carbon sequestration in India. *Climatic Change,* 65, 277-296.

Lal, R., Kimble, J.M., Follett, R.F., & Cole, C.V. (1998). *The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect*. Chelsea, Mich.: Ann Arbor Press.

Mahapatra, B.S., Sharma, G.L., & Singh, N. (1991). Integrated management of straw and urea nitrogen in lowland rice under a rice - wheat rotation. *Journal of Agricultural Science,* 116, 217-220.

Mandal, B., Majumder, B., Bandopadhyay, P.K., Hazra, G.C., Gangopadhyay, A., Samantaroy, R.N., Misra, A.K., Chowdhuri, J., Saha, M.N., & Kundu, S. (2007). The potential of cropping systems and soil amendments for carbon sequestration in soils under long-term experiments in subtropical India. *Global Change Biology,* 13, 357-369.

Matus, F.J., Lusk, C.H., & Maire, C.R. (2008). Effects of soil texture, carbon input rates, and litter quality on free organic matter and nitrogen mineralization in Chilean rain forest and agricultural soils. *Communications in Soil Science and Plant Analysis,* 39, 187-201.

Nambiar, K.K.M. (1995). Major cropping systems in India. In V. Barnett, R. Payne, R. Steiner (Eds.), *Agricultural sustainability: Economic, environmental and statistical considerations*. (pp. 133-170). London: Wiley.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar, Sonali. P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research,* 127, 129-139.

Olk, D.C., Cassman, K.G., Randall, E.W., Kinchesh, P., Sanger, L.J., & Anderson, J.M. (1996). Changes in chemical properties of organic matter with intensified rice cropping in tropical lowland soil. *European Journal of Soil Science*, 47, 293-303.

Purakayastha, T.J., Rudrappa, L., Singh, D., Swarup, A., & Bhadraray, S. (2008a). Long-term impact of fertilizers on soil organic carbon pools and sequestration rates in maize–wheat–cowpea cropping system. *Geoderma,* 144, 370-378.

Purakayastha, T.J., Huggins, D.R., & Smith, J.L. (2008b). Carbon sequestration in native prairie, perennial grass, no-tilled and cultivated Palouse silt loam. *Soil Science Society of America Journal,* 72, 534-540.

Qadir, M., Qureshi, R.H., & Ahmad, N. (2002). Amelioration of calcareous saline-sodic soils through phytoremediation and chemical strategies. *Soil Use and Management,* 18, 381-385.

Ram, N. (1998). Effect of continuous fertilizer use on soil fertility and productivity of a *Mollisol*. In A. Swarup, R.D. Damodarand, R.N. Prasad (Eds.), *Long-term soil fertility management through integrated nutrient supply*. (pp. 229-237). Bhopal, India: Indian Institute of Soil Science.

Rudrappa, L., Purakayastha, T.J., Singh, Dhyan., & Bhadraray, S. (2006). Long-term manuring and fertilization effects on soil organic carbon pools in a *typic haplustept* of semi-arid sub-tropical India. *Soil and Tillage Research*, 88, 180-192.

Sahrawat, K.L. (2004). Organic matter accumulation in submerged soils. *Advances in Agronomy,* 81, 169-201.

Sidhu, B.S. & Beri, V. (1989). Effect of crop residue management on the yields of different crops and on soil properties. *Biological Wastes,* 27, 15-27.

Singh, B. (1996). Influence of forest litter on reclamation of semiarid sodic soils. *Arid Soil Research and Rehabilitation*, 10, 201-211.

Singh, G. & Singh, N.T. (1997). Effect of land use practices on organic carbon dynamics of sodic soils. In R. Lal, J. Kimble, R. Follett (Eds.), *Soil properties and their management for carbon sequestration*. (pp. 89-105). USDA-Natural Resources Conservation Service, National Soil Survey Centre.

Smith, P., Powlson, S.D.S., Glendining, M.J., & Smith, J.U. (1997). Potential for carbon sequestration in European soils: Preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology,* 3, 67-79.

Tandon, H.L.S. (1997). Organic residues: An assessment of potential supplies, their contribution to agricultural productivity and policy issues for Indian agriculture from 2000 to 2025. In I.S. Kanwar, S.C. Katyal (Eds.), *Plant nutrient needs, supply, efficiency and policy issues: 2000–2025*. New Delhi, India: National Academy of Agricultural Sciences.

Verma, T.S., & Bhagat, R.M. (1992). Impact of rice straw management practices on yield, nitrogen uptake and soil properties in a wheat–rice rotation in northern India. *Fertilizer Research,* 33, 97-106.

Watanabe, I. (1984). Anaerobic decomposition of organic matter. In *Organic matter and rice*. (pp. 2377-258). Manila, Philippines: International Rice Research Institute.

White, J.W., & Rodriguez-Aguilar, A. (2001). An agroclimatological characterization of the Indo-Gangetic Plains. *Journal of Crop Production,* 3, 53-65.

Wong, V.N.L., Greene, R.S.B., Dalal, R.C., & Murphy, B.W. (2010). Soil carbon dynamics in saline and sodic soils: A review. *Soil Use and Management,* 26, 2-11.

Yadav, R.L. & Subba Rao, A.V.M. (2001). *Atlas of cropping systems in India.* (pp. 96). Modipuram, Meerut, India: Project Directorate for Cropping Systems Research.

Yadav, R.L., Dwivedi, B.S., & Pandey, P.S. (2000). Rice–wheat cropping system assessment of sustainability under green manuring and chemical fertilizer inputs. *Field Crops Research,* 65, 15-30.

Zhang, W., Xu, M., Wang, B. & Wang, X.J. (2009). Soil organic carbon, total nitrogen and grain yields under long-term fertilizations in the upland red soil of southern China. *Nutrient Cycling in Agroecosystems,* 84, 59-69.

*****

Chapter 6

Soil organic carbon pools and productivity in rice based cropping system

M.C. Manna[1*], P. Bhattacharyya[2], T.K.Adhya[2] and A. Subba Rao[1]
[1]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[2]Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: madhabmc@yahoo.com

Despite impressive gains in cereal production by India, from 50 m t in 1947 to more than 219 m t in 2000, that remain serious problem. One, expected food demand by 2050 is 300 million tonnes of cereals and must be met from the shrinking land resource base. There are severe problems of degradation of soil and water resources leading to reduction in use efficiency of inputs (e.g., fertilizer, irrigation, tillage), pollution of surface and ground waters, and emission of greenhouse gases (GHGs) from soil/terrestrial/aquatic ecosystems into the atmosphere. Soil organic carbon (SOC) play multifunctional role to improve this degradation. The majority of carbon is held in the form of SOC, having a major influence on soil structure, water holding capacity, cation exchange capacity, the soils ability to form complexes with metal ions to store nutrients, improve productivity, minimize soil erosion, etc. This organic carbon is highly sensitive to changes in land use and management practices such as increased tillage, cropping systems, fertilization, etc., leading to SOC decline. Conversely, land use change and the appropriate management of soils also provide us with the potential to sequester carbon in soils.

It is a well recognized fact that soil organic matter (SOM) is of fundamental importance in soil fertility. It is a storehouse of all essential plant nutrients and provides energy material for the soil organisms. The maintenance of SOM in agricultural soils is primarily governed by climate, particularly annual precipitation, temperature and cropping practices. Although amount of SOM in soils of India is relatively low (ranging from 0.1 to 1.0% and typically less than 0.5%), its influence on soil fertility and physical condition is of great significance. Conversion of land from its natural state to agriculture generally leads to loss of SOM. The maintenance of SOC in tropical soils to a desirable level of 0.5 to 1% is extremely important for sustainable crop production. It may take up to 50 years for the organic matter of soils in the temperate climate to reach a new equilibrium level following a change in management, but this time period is much shorter in the semiarid and tropical environment like India. Intensive cropping and tillage systems have led to substantial decrease in the SOM levels under semiarid and sub-humid regions, through enhanced microbial decomposition, wind and water erosion of inadequately protected soils. This decrease in SOM level has often been accompanied with the decline of soil productivity.

Change in carbon (C) and nitrogen (N) content reflects in change in total SOM. These are slow processes, which are measurable only over the period of decades. Investigation on SOM dynamics therefore, requires long-term experiments with treatments that emulate major regional soil use and management systems. These experiments offer ideal opportunity to define soil quality indicators which are sensitive to changes in SOM. Studies on the quantitative changes in SOM content under rain fed areas are available but investigations on SOM turnover, the mean residence time of different SOM pools and ecological impacts are not available. Therefore, there is a need to examine the SOM dynamics under sub-humid conditions of rice based cropping system.

So far literature on SOM changes in rain fed semiarid and sub-humid regions did not throw much light on the carbon functional pools, which are highly sensitive indicator of soil fertility and productivity. The distribution of soil organic matter into following five functional pools may be made for its true representation.

1. Structural litter fraction: This consists of straw, wood, stems and related plant parts. The C: N ratio varies around 150:1. These are high in lignin content.
2. Metabolic pool fraction: It comprises plant leaves, bark, flower, fruits and animal manure. The C: N ratio ranges from 10 to 25. This fraction gives up mineral nitrogen as it is decomposed with loss of carbon dioxide (CO_2).
3. Active pool of soil carbon: This is microbial biomass and their metabolites. The C:N ratio is around 5 to 15. This fraction gives up mineral nutrients and it gives life to the soil. Besides soil microbial biomass carbon (SMBC), light fraction of organic matter, water-soluble carbon and water -soluble carbohydrates are also active pools of organic matter.
4. Slow decomposable soil fraction: This fraction is comparable to nature of composting having C: N ratio around 20:1. It makes temporary stable humus in soil, which is slowly decomposable.
5. Passive soil organic fraction: This is the highly recalcitrant organic matter with C:N ratio of 7:1 to 9:1. It is resistant to oxidation and is not readily involved in dynamic equilibrium with other types of organic fractions in soil.

The specific relationship of management practices and biologically active SOM with soil process is not well characterized. The structure of SOC sub-model is illustrated in Century Model (Fig. 1) (Parton et al., 1987). This model includes respiration C losses associated with dynamics of organic pools. Similarly, the N- sub models have the same basic structure of SOM and also include the flow of nutrients in different mineral form. Moreover, SOC turnover is dependent on soil moisture, radiation, temperature, cropping, rooting and plant residue, etc. Combine effect of all these factors on the dynamics of SOM is not yet established in tropics. Studies therefore, need to be conducted to develop a model of SOM for rain fed rice-based cropping systems which will include different parameters such as physical properties of soil, nutrient status, light fraction of SOC, hot water -soluble carbon, soil microbial biomass carbon (SMBC), activity of enzymes, etc. Such model may be of great practical importance from management point of view and as an indicator of soil quality in climatic change scenario.

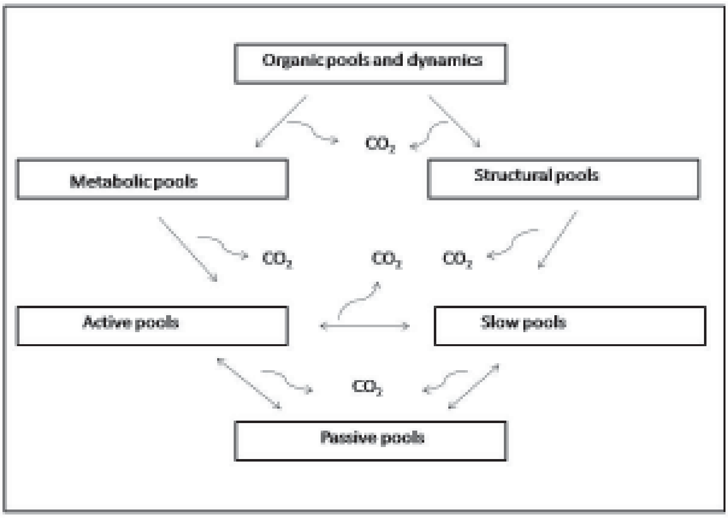


FIGURE 1. *Soil organic carbon sub-model in Century*

Long term fertilizer experiments conducted in India have clearly brought out the fact that the balanced use of plant nutrients is important to sustain crop productivity and soil fertility. Under intensive cropping with imbalanced fertilizer use particularly N alone, SOM content showed a decline irrespective of cropping systems and soil types. So far little information is available under different soil crop management systems on different pools of carbon, which is highly sensitive indicator of soil fertility and productivity.

Thus, one needs to understand how land use and management practices such as fertilization and tillage in rice based cropping systems can potentially enhance C-pools, C-sequestration and SOC storage equilibrium over a period of cultivation and these aspects are discussed in this chapter.

Soils carbon pool

In general, SOC concentration increases with increase in clay content and rainfall, and decreases with increase in mean annual temperature. Some of these soils have been cultivated for centuries, and often with low off-farm input, based on systems that involve removal of crop residue and cow dung for fuel and other purposes. Diverse soils are also characterized by a wide range of SOC concentration, which is generally related to clay content (Ali et al., 1966) and climate (Jenny & Raychaudhary, 1960). The data in Table 1 show that SOC concentration of most soils is less than 10 g kg^{-1}, and is generally less than 5 g kg^{-1}. Because of the low clay contents, the SOC concentration is especially low in alluvial soils of the Indo-Gangetic Plains, coarse-textured soils of southern India, and arid zone soils of northwestern India. The low levels of SOC concentrations are attributed to excessive tillage, imbalance in fertilizer use, little or no crop residue returned to the soil, and severe soil degradation.

TABLE 1. *Depletion of soil organic carbon concentration of cultivated compared with that in undisturbed soils (adapted from Jenny & Raychaudhary, 1960; Swarup et al., 2000)*

Region	SOC content		Percent reduction
	Cultivated (g kg^{-1})	Native (g kg^{-1})	
1. Northwest India			
Indo-Gangetic Plains	4.2 ±0.9	10.4 ± 3.6	59.6
Northwest Himalaya	24.3 ± 8.7	34.5 ± 11.6	29.6
2. Northeast India	23. 2 ± 10.4	38. 3 ±23. 3	39.4
3. Southeast India	29.6 ± 30. 1	43.7 ± 23.4	32.3
4. West coast	13.2 ±8.1	18.6±2.1	29.1
5. Deccan Plateau	7.7 ±4.1	17.9 ±7.6	57.0

The principal cause of decline in SOC pool in degraded soils is a reduction in biomass productivity and the low amount of crop residue and roots returned to the soil. A typical example of the low SOC pool is in salt-affected soils of Haryana, Andhra Pradesh, Odisha and West Bengal. Even in the surface 0 - 15 cm layer, the SOC pool may be lower than 5 g kg^{-1}.

Accelerated soil erosion depletes the SOC pool severely and rapidly. The SOC fraction is preferentially removed by surface runoff and wind because it is con-centrated in the vicinity of the soil surface and has low density (1.2 to 1.5 Mg m^{-3} compared with 2.5 to 2.7 Mg m^{-3} for the mineral fraction). The effectiveness of several techniques for SOC sequestration has been discussed by Swarup (1998) and Swarup et al. (2000), and is outlined in Table 2. Swarup (1998) reported the impact of integrated nutrient management, including application of NPK and manuring (8 - 10 Mg $ha^{-1}y^{-1}$), on SOC concentration in surface layer of soils from long term rice based experiments established in different ecoregions of India. Assuming a plough depth of 20 cm and soil bulk density of 1.4 Mg m^{-3}, the rate of SOC sequestration was calculated for NPK + manuring over that of the control. The results showed low rates of C change over, 15 to 120 kg C ha^{-1}y^{-1}. The low rates are attributed to low soil water, high soil temperature and high rate of oxidation (Table 2).

TABLE 2. *Effect of soil fertility management on SOC concentration in a long term manuring experiment (recalculated from Swarup. 1998) (assuming plough depth of 20 cm and bulk density of 1.4 Mg m^{-3})*

Location	Soil	Initial (g kg^{-1})	Control (g kg^{-1})	NPK (g kg^{-1})	NPK + FYM (g kg^{-1})	Period (yrs)	Rate of change over control (kg C ha^{-1}y^{-1})
Barrackpore (Rice-wheat-jute)	Eutrochrept	7.0	4.1	5.0	5.4	24	15
Bhubaneswar (Rice-rice)	Haplaquept	2.6	3.7	5.7	8.1	21	59
Hyderabad (Rice-rice)	Tropaquept	5.0	4.6	5.3	8.0	23	41
Pantnagar (Rice-rice)	Hapludoll	13.0	5.0	8.3	15.0	24	117

Yield trends and soil organic carbon

The yield trends and total organic carbon over 30 years of multiple rice-based cropping systems in an Inceptisol of West Bengal are given in Table 3. Linear regression analysis showed negative yield trends of rice based cropping system was due to repeated application of imbalance fertilizer in a long run. Similarly, the declining trends were also observed in total organic matter content in these treatments over the initial value (Table 4). It is interesting to note that though positive trends of total organic carbon (TOC) were observed in NPK and NPK+FYM treatments but improved yields were not obtained over the years.

TABLE 3. *Long term effect of manure and fertilizers on yield trends in rice based cropping system*

Locations	Treatments	Rate of yield change: Magnitude (Mg ha^{-1}yr^{-1})	*t*-stat	*p*-value	Initial value[a] (Mg ha^{-1})	Sustainable yield index (SYI)
Barrackpore						
Rice	Control	-0.028	-3.410	0.002	1.93	0.16
	N	-0.087	-6.032	0.000	4.49	0.33
	NP	-0.081	-4.972	0.000	4.75	0.38
	NPK	-0.090	-5.753	0.000	5.03	0.40
	NPK+FYM	-0.060	-3.958	0.000	4.81	0.47
	LSD 5%	-	-	-	-	0.04
Wheat	Control	-0.013	-3.067	0.005	0.95	0.14
	N	-0.036	-4.550	0.000	2.50	0.41
	NP	-0.021	-2.225	0.034	2.55	0.49

Contd....

Locations	Treatments	Rate of yield change			Initial value[a] (Mg ha^{-1})	Sustainable yield index (SYI)
		Magnitude (Mg ha^{-1}yr^{-1})	*t*-stat	*p*-value		
	NPK	-0.017	-1.913	0.066	2.56	0.52
	NPK+FYM	-0.021	-2.209	0.035	2.67	0.55
	LSD 5%	-	-	-	-	0.034
Jute	Control	-0.118	-2.318	0.028	3.20	0.20
	N	-0.040	-6.827	0.000	2.90	0.47
	NP	-0.038	-8.254	0.000	2.35	0.51
	NPK	-0.032	-7.576	0.000	2.47	0.61
	NPK+FYM	-0.011	-2.382	0.024	2.30	0.70
	LSD 5%	-	-	-	-	0.04

[a] Intercept value is considered as initial value (Manna et al., 2005a)

TABLE 4. *Long term effect of manure and fertilizers on SOC trends in rice based cropping system*

Location	Treatment	Rate of SOC change			Initial value (g kg^{-1})[a]
		Magnitude (g kg^{-1} yr^{-1})	*t*-stat	*p*-value	
Barrackpore (Rice–wheat-jute)	Control	-0.028	-0.364	0.025	5.30
	N	-0.044	-5.770	0.000	6.35
	NP	-0.017	-1.540	0.123	4.98
	NPK	0.078	5.880	0.000	4.64
	NPK + FYM	0.066	5.250	0.000	5.05

[a] Intercept value is considered as initial value

Active pools of carbon

The active fractions of SOC (Soil microbial biomass carbon (SMBC), Water soluble carbon (WSC), Acid Hydrolysable Carbohydrates (AHC)) changed significantly and substantial amount of these parameters decreased under N or NP treatments as compared to balanced NPK use. Most of the researches specifically emphasized upon SOC and its pool fractions (active and slow pools), which lead to improved soil fertility, sustainability and environmental quality. More information is also required whether collapsing of active fraction of C and N of SOM hamper the nutrients supply in long run. In the imbalanced fertilized plots (N and NP), SMBC decreased about 1.1-3 folds compared to NPK+FYM application in rice based cropping system. Acid hydrolysable carbohydrate is a labile C fraction and has been found to change more rapidly in response to changes in management than SOC contents. The biological activity of soil causes the large amount of soil microbial biomass is soil and also more labile component of SOM fractions (soluble phase of carbon and carbohydrates) than most other fractions.

Yield declining/ or stagnating in long-term experiments could occur because of many factors such as decline of SOM and associated nutrients, imbalanced fertilizer application, climate, insect pest and crop management practices. It is also evident that yield declined in NPK despite the fact that total organic carbon (TOC) was maintained in this treatment (Table 3). This study clearly indicates that TOC stock is not necessarily related to yield decline. After 31 years of continuous cultivation (1971-2001) study on the active pools of C and N indicated a gradual decline over initial level. Continuous N, NP or NPK fertilizer application were prone to large N losses because of alternate wetting (anaerobic) and drying (aerobic) conditions during rice cultivation. Total organic C improved in NPK and NPK plus FYM treatment. The total C and N pools in these treatments however, were maintained suggesting that regular application of organic matter with NPK is critical for their maintenance in the rice-based cropping system.

Although active pool is a small fraction of SOM, it is considered as buffering agent and found useful in replenishment mechanisms like desorption from soil colloids, dissolution from litter, and exudation from plant roots. The contribution of water-soluble fractions in the inorganic fertilized treatment was less because aboveground biomass was neither used nor returned to the soil in any form in rice based cropping system. The reduced amount of active pools of C and N after long term cultivation of fertile virgin soil leads to depletion of soil fertility in three ways i.e. through reduced labile sources of nutrients; reduced rate of mineralization, and lower bioavailability of nutrients. Furthermore, continuous cultivation with cereal based cropping reduced total amount of nutrients as well as soil microbial biomass, which could lead to biological degradation of soil. Similarly, continuous application of inorganic fertilizer and removal of aboveground biomass significantly reduced not only total amount of nutrients but also the active pools of C and N resulting in decline of crop yields. It is often difficult to maintain or enhance the organic matter and N in cultivated soil unless a cover/legume crop is included in the rotation or a heavy application of manures and crop residues is made. Therefore, balanced plant nutrition (fertilizer in combination with manure) every year may contribute more labile fraction of C, which acts as a source of bioenergy and helps to improve mineralization process.

Soil TOC and total nitrogen (TN) concentration in bulk soil samples of the unfertilized control from the topsoil (0-15 cm) lost approximately one-third of its original TOC and two-third of its initial total N concentration (7.12 g TOC kg^{-1} and 960 mg N kg^{-1} soil, 1971) (Table 1). Microbial biomass is an essential component of labile C. Sometimes it is used as a surrogate for labile C pools, because it can readily be determined through physical and biochemical method. The MBC and microbial biomass nitrogen (MBN) in the treatment receiving FYM with fertilizer NPK were about 35 to 52 % and 32.8 to 44 % more than in N, NP and NPK treatments and approximately 1.5 and 1.3 times higher than fallow soils. The results showed that MBC ranged from 3.3 to 7.3 % of total organic carbon and MBN from 1.1 to 2.3 % of total N in the surface layer. The water soluble fraction is considered the most active part of TOC and on an average the WSC and water soluble nitrogen (WSN) accounted for 0.2 to 1.4% of TOC and 1.0 to 2.6% of TN, whereas hydrolysable carbohydrates accounted for 9.2 to 11.3% TOC in the top surface layer (Table 5).

TABLE 5. *Long term effect of manure and fertilizer application on active fractions of soil organic carbon under Inceptisol (Rice-wheat-jute) at 0-15 cm soil depth*

Location	Treatment	SMBC ($g\ m^{-2}$)	SMBN ($g\ m^{-2}$)	AHC ($g\ m^{-2}$)	WSC ($mg\ kg^{-1}$)	% POM in SOC
Inceptisol	Control	33.8	2.28	105.2	10.7	10.6
(Rice-wheat-jute)	N	32.4	2.14	116.0	12.6	16.5
	NP	41.8	2.20	121.8	26.3	22.4
	NPK	65.4	2.20	137.8	69	20.0
	NPK+FYM	97.2	4.04	169.0	80.4	27.0

SMBC: Soil microbial biomass carbon; WSC: Water soluble carbon; AHC: Acid Hydrolysable Carbohydrates (Manna et al., 2005b)

Slow pool of carbon

In general, the aggregates size distribution was dominated by micro-aggregates (53 - 250 μm) followed by small macro-aggregates (250 to 2000 μm) in most of the rice–based cropping systems in Inceptisols. Alternate wetting (anaerobic) and drying (aerobic) condition resulted after continuous intensive conventional tillage operations and removal of aboveground residues induced a rapid mineralization of aggregates associated SOM which collapsed the aggregates (>2-mm diameter size class). The correlation between reduction in aggregates and loss of SOM with cultivation has been used to explain aggregate hierarchy theory by many authors (Camberdella and Elliott, 1993; Six et al., 2000). Increasing cultivation intensity with repeated application of inorganic fertilizers (N, NP and NPK) caused reduction of macro-aggregates (Manna et al., 2005b, 2007a and 2007b). It is because of no significant release of water-soluble carbon and hydrolysable carbohydrates (which acted as binding agents) from belowground biomass decomposition upon microbial action. This perhaps resulted in loss of soil aggregates.

As cultivation continued with N, NP and NPK fertilization, there was a extensive depletion of organic matter associated with particulate organic matter carbon (POMC), light fraction carbon (LFC) and light fraction nitrogen (LFN). Light fraction carbon and LFN originating from stubbles biomass and root biomass in cultivated soil were mostly affected by both residue input and soil micro-climatic conditions. Free-light fractions are more labile organic matter slow pools but constitutes partially decomposed organic matter. The free LFC and N seems to be the POM fraction that is especially affected by residue input, whereas other fractions are affected by aggregation and aggregate mineralization. The free LF decomposition rate has been influenced by soil moisture, temperature, crop residue, quality and quantity of input whereas POM disruption rate is primarily affected by only soil aggregations. Particulate organic matter carbon is mostly used as an indicator of soil quality caused by land use management and tillage. Particulate organic matter carbon made up of 16.4 to 28% of TOC and tended to increase under NPK plus FYM than NPK treatment (Table 6). The percentages of soil C present in the free light fraction and POM in the top 0 to15cm depth of cultivated soils were 1.6 to 2.5 and 16.4 to 28.0% of TOC, respectively. Particulate organic matter nitrogen comprised 5.1 to 15.9% of TN. Therefore, 69.5 to 82.4% of TOC was present in the mineral associated organic matter in these treatments. It was observed that continuous application of N, NP or NPK for 30 years reduced the POMC by 5.3 to 10.7% of TOC and 5.3 to 29.5% of TN compared to fallow soil. The results clearly revealed that improvement of POM, could be associated with improvement of soil physical properties, microbial activities and better supply of plant nutrients. The C mineralization was lower than N mineralization either

TABLE 6. *Effect of manure and fertilizer on LF-C, LF-N, POM-C, POM-N and mineral associated-C and mineral associated-N (0-15cm depth)*

Treatments	LF-C (mg kg^{-1})	LF-N (mg kg^{-1})	LF-C/ LF-N	POM-C (g kg^{-1})	POM-C/ TOC	POM-N (g kg^{-1})	POM-N/ TN	Mineral Associated-C	Mineral Associated-N
Fallow	120	11.5	10.3	1.53	25	118.48	10.3	4.4	0.492
Control	61	8.2	7.6	0.54	9	24.60	5.1	4.6	0.388
N	91.5	9.8	9.1	0.94	13.8	84.7	12.1	4.7	0.570
NP	99	11.3	9.6	1.41	22.4	96.3	13.7	4.8	0.630
NPK	120	10.9	11.2	1.48	20.0	112.3	11.7	5.8	0.747
NPK+FYM	212	15.6	13.8	2.19	27.38	141.2	15.9	5.5	0.770

POMC: Particulate organic matter carbon; LFC: Light fraction carbon; LFN: Light fraction nitrogen (Manna et al., 2005b) from slow pools (aggregate size classes) or from mineral–associated organic matter (silt + clay) fraction (Manna et al., 2005b). Further, they reported that less mineralization rate in micro-aggregates may be due to transformation of labile materials to more stable fractions during continuous cultivation. The treatments variation of decay rate constant was due to quantity of LFC and LFN as well as POMC present in each aggregates size classes. However, more research is required to explain whether significant fraction of labile materials are transformed to stable fraction during different land use management system that may eventually effect nutrient supply to plants. The best approach should be the integrated use of manure and fertilizer in the highly intensive rice based cropping system to maintain SOC. The practice of residue incorporation during transition period of two crops is difficult. For example, after harvest of rice the transitional gap is only 20 to 25 days prior to wheat sowing. There is scope of further investigation to explain as to how residue can be managed in a short period without scarifying the next crop so that regular addition of residue along with balance fertilizer maintain active and slow pools of C and N under high intensive cropping system in a long run. Perturbations to the soil system such as conversion of native vegetation to arable agriculture cause large changes in SOM content in soil. Particulate organic matter carbon is the precursor for formation of soil microbial biomass carbon, soluble fraction of carbon, humic and non-humic fraction of carbon in soil and thus it is a key attribute of soil quality. It is the major source of cellular C and energy for the heterotrophic microorganisms. The POM accumulation is also the major pathway by which nutrients are recycled from crop residues back to the soil and release nutrients by mineralization during decomposition of POM. The large amount of microbial community associated with the decomposing POM produces binding agent such as exocellular mucilaginous polysaccharides. It acts as a major food and energy for endogenic soil fauna. Thus, POM is associated with a multitude of soil process and functions and is therefore, a key attribute of soil quality.

Carbon sequestration rate and efficiency in rice based cropping system

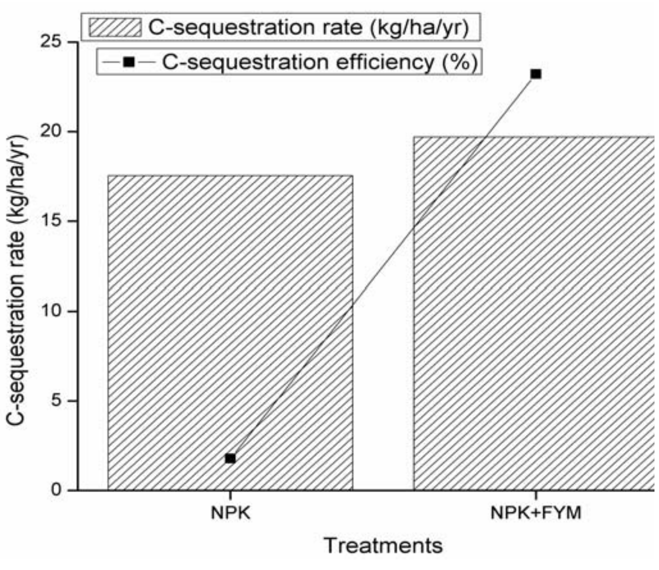


FIGURE 2. *Carbon sequestration rate and efficiency in Inceptisol (Manna et al., 2012)*

It was observed that all the long term imbalanced fertilizer treatments were not encouraged for carbon sequestration rate and carbon sequestration efficiency in rice based cropping system. For example, in Inceptisol at Barrackpore the treatments with NPK and NPK+FYM showed lower carbon sequestration rate and it was varied from 17 to 22 kg ha^{-1}yr^{-1} and C-sequestration efficiency was varied from 0.42 to 0.45 % in these treatments (Fig. 2).

Carbon steady state and carbon turnover

Using a non-linear regression model, the steady state SOC$_e$ and loss rate k of the surface (0-15 cm) over 30 years of continous cultivation were calculated (Table 7). While calculating carbon steady state, it was assumed that the maximum amount of biomass C from leaf fall, stubbles and root remained on the surface layer. The values of SOC_o (calculated) were not close to mean SOC values of the initial samples (measured) for Inceptisol. Because, initially the total C decreased rapidly in the first 10 years and then stabilized in later stage in Inceptisols. If the above situation occurs in any system, the SOC_e value of cultivated soils happens to be similar to the SOC_o value in the model. After fitting the model the negative k values indicate the tendency of positive C over a period, with a new equilibrium. Higher SOC_e values indicate a decline in the total SOC whereas higher negative k values means decline occur in the shorter period. The SOC loss rate in different treatments varied considerably from 0.020 to 0.129 per year in Inceptisol (Table 7). This study clearly indicates that application of NPK+FYM had the lowest turn over period (t=1/k, 7.7 years in Inceptisol) when compared to other treatment under a high intensive cropping system in long run.

TABLE 7. *Initial status of organic carbon and equilibrium values for different treatments after 31 years of cultivation (Barrackpore)*

Treatment	Initial SOC ($g\ kg^{-1}$)	SOC_o ($g\ kg^{-1}$)	Steady state mean ($g\ kg^{-1}$)	Loss rate SOC_e ($g\ kg^{-1}$)	$t_{1/2}$ (yr^{-1})	R^2
N	7.12	4.99 ± 0.025	4.8 ± 0.018	-0.020	50.3	0.10
NP	7.12	4.99 ± 0.065	5.0 ± 0.022	-0.067	14.9	0.22
NPK	7.12	5.0 ± 0.038	5.1 ± 0.04	-0.095	10.7	0.39
NPK + FYM	7.12	5.4 ± 0.022	5.6 ± 0.017	-0.129	7.7	0.62**

** Value is significant at $p< 0.05$; ± standard error (Manna et al., 2012)

Passive pools of carbon

In rice based cropping system the changes in humic acid (HA) concentrations and HA/fluvic acid (FA) ratios were higher in the surface soil (0-15cm) and decreased with increase in depths (Manna et al., 2005b). On the contrary, FA-concentrations were higher at lower depth compared to surface soil. The HA and FA content did not vary due to treatments. Similarly, HA and FA ratios also did not vary due to treatments. Acid hydrolysable-N of humic substances was lower in HA-N than FA-N irrespective of treatments indicating that more time frame is required to improve passive fraction of C.

Conclusions

Rice based cropping systems are predominant in the Indo-Gangetic Plains of India and other South Asian countries. The annual rotation such as rice -wheat, rice-wheat-jute and rice-rice are dominant cropping system in India. Most of long term experiments with rice based cropping system, the yield trends of rice were negative in imbalanced fertilized plots due to loss of active and slow pools of carbon, quantity and quality of soil organic matter pools with associate nutrients and deterioration of physical properties of soil. Further, extensive tillage operation significantly reduced macro-aggregates in imbalanced fertilized plots and resulted in significant reduction of light fraction of particulate organic carbon and heavy fraction of particulate organic matter carbon. These fractions were improved by NPK+FYM treatment. Carbon sequestration efficiency and C-sequestration rate were also improved in NPK+FYM treatment under rice based cropping system. Various results suggest that the integrated use of NPK and FYM is important for sustaining this cropping system.

References

Ali, M.H., Chaterjee, R.K., & Biswas, T.D. (1966). Soil moisture tension relationship of some India soil. *Journal of the Indian Society of Soil Science*, 14, 51-62.

Camberdella, C.A., & Elliott, E.T. (1993). A carbon nitrogen distribution in aggregates from cultivated and native grass land soils. *Soil Science Society of the American Journal*, 57, 1071-1076.

Jenny, H., & Raychaudhuri, S.P. (1960). *Effect of climate and cultivation on nitrogen and organic matter reserves in Indian soils*. (pp. 1-125). New Delhi: Indian Council of Agricultural Research.

Manna, M.C., Swarup, A., Wanjari, R.H., Ghosh, P.K., Singh, K.N., Singh, Y.B., Tripathi, A.K., & Saha, M.N. (2005a). Soil organic matter in a West Bengal *Inceptisol* after 30 years of multiple cropping and fertilization. *Soil Science Society of America Journal*, 70, 121-129.

Manna, M.C., Swarup, A., Wanjari, R.H., Ravankar, H.N., Mishra, B., Saha, M.N., Singh, Y.V., Sahi, D.K., & Sarap, P.A. (2005b). Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. *Field Crops Research*, 93, 264-280.

Manna, M.C., Swarup, A., Wanjari, R.H., Mishra, B., & Sahi, D.K. (2007a). Long-term fertilization, manure and liming effects on soil organic matter and crop yields. *Soil and Tillage Research*, 94, 397-409.

Manna, M.C., Swarup, A., Wanjari, R.H., & Ravankar, H.N. (2007b). Long-term effect of NPK fertilizer and manure on soil fertility and a sorghum-wheat farming system. *Australian Journal of Experimental Agriculture*, 47, 700-711.

Manna, M.C., Sahu, A., & Subba Rao, A. (2012). Impact of long-term fertilizers and manure application on C-sequestration efficiency under different cropping systems. *Journal of Soil and Water Conservation (In press).*

Parton, W.J., Schimel, D.S., Cole, C.V., & Ojima, D.S. (1987). Analysis of factors controlling soil organic matter levels in Great Plains grassland. *Soil Science Society of America Journal*, 51, 1173-1179.

Six, J., Paustian, K., Elliott, E.T., & Combrink, C. (2000). Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregates-associated carbon. *Soil Science Society of America Journal*, 64, 681-689.

Swarup, A., Manna, M.C., & Singh, G.B. (2000). Impact of land use management practices on organic carbon dynamics in soils of India. In R. Lal et al. (Eds.), *Global climate change and tropical ecosystems: Advances in soil science (USA).* pp. 261-281.

Swarup, A. (1998). Emerging soil fertility management issues for sustainable crop productivity in irrigated systems. In *Long-term soil fertility management through Integrated Plant Nutrient Supply System.* (pp1-335). Proceedings of National workshop. April 2-4. Bhopal, India: Indian Institute of soil Science.

*****

Chapter 7

Impact of elevated carbon dioxide on soil microbial activity

S. Karthikeyan*, D.Balachandar and K.Chendrayan
Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India
*e-mail: s.karthy@gmail.com

Since the late 18th century fossil fuel use, expansion of cultivated agriculture and deforestation has led to an increase in atmospheric carbon dioxide (CO_2) from 280 ppm to current of 379 ppm (Keeling & Whorf, 1998; IPCC, 2007). As a consequence, carbon as CO_2 is currently accumulating in the atmosphere at a rate of 3.5 billion tonnes yr^{-1}. Carbon dioxide is the most important greenhouse gases (GHGs), accounting for about half of the greenhouse effect. The natural concentration of GHGs has been essential for life. However, human activities such as burning fossil fuels, the chemical industry, agriculture and land use changes are responsible for increasing the amount of GHGs, especially CO_2 in the atmosphere.

The result of all this is an increased GHGs and raised global temperature by 0.5°C over the past 100 years. As a result of human-induced increases in GHGs, the temperature is projected to increase by 1 to 5°C during the next 100 years. One degree celsius increase in temperature may result in drastic change in vegetation zones moving toward the poles by 200 to 300 km and also increase water evaporation and extremes in floods and droughts and imbalanced the terrestrial ecosystems. Hence, focusing on the microbial profile changes in soil due to the flux of GHGs helps developing appropriate soil management practices.

The response of terrestrial ecosystems to CO_2 fertilization is linked to belowground processes, particularly those performed by microorganisms (Zak et al., 2000a). The genetic structure and the functionality of soil microbes are both important when studying the role of soil in the carbon (C) cycle. Greater belowground C inputs from plants growing under elevated CO_2 have been widely observed in the literature (Bernston & Bazzaz, 1996; Hoosbeek et al., 2006) and these inputs are thought to stimulate microbial activity.

Microbial biomass carbon

Numerous studies have failed to find a significant response of microbial biomass C to elevated CO_2 (Jones et al., 1998; Kampichler et al., 1998; Niklaus, 1998; Insam et al., 1999; Hungate et al., 2000, Wiemken et al., 2001; Larson et al., 2002; Montealegre et al., 2002; Mitchell et al., 2003). Wiemken et al. (2001) showed that the amounts of C (a general marker for microbial biomass) and chitin (a marker for fungal biomass) did not respond significantly to the treatments with elevated CO_2 or nitrogen fertilizer. Schortemeyer et al. (1996) reported that the size of the total heterotrophic microbial populations, in the form of microbial C in the rhizosphere of white clover or perennial ryegrass, did not change under elevated CO_2. In a more recent study, Schortemeyer et al. (2000) reported that microbial biomass did not increase in a natural Florida scrub ecosystem after 2 years of CO_2 enrichment. In an artificial tropical ecosystem with low nutrient availability, Insam et al. (1999) reported that microbial biomass C, ergosterol contents, and fungal hyphal lengths were not significantly altered by high CO_2 concentration, although total bacterial counts were significantly higher. Zak et al. (2000b) found that microbial biomass remained unchanged in bulk soils under elevated CO_2 after 2.5 growing seasons. Niklaus (2001) analyzed ecosystem C partitioning and soil C fluxes in grassland exposed to elevate CO_2 for 6 years. They showed that C pools increased in plants (+23%) and surface litter (+24%), but were not altered in microbes and soil organisms. However, several studies conflict with such observations, and have reported an increase in soil microbial biomass under elevated CO_2 (Diaz et al., 1993; Zak et al., 1993; Dhillion et al., 1996; Pregitzer et al., 2000, Williams et al., 2000; Klamer et al., 2002). Zak et al. (1993) observed that microbial biomass C in the rhizosphere and bulk soil of *Populus grandidentata* was greater under elevated than ambient CO_2. In an acidic grassland herbaceous community a an increase of up to 80% in microbial biomass C occurred under elevated CO_2 (Diaz et al., 1993). Dhillion et al. (1996) reported that microbial biomass C was significantly higher in root region of soil from monocultures of *Bromusmadritensis*, a common and sometimes dominant annual grass in Mediterranean model ecosystem plants under elevated CO_2. Montealegre (2002) reported that bacterial populations increased about 1.4 fold under white clover after 3 years of CO_2 fumigation in pasture ecosystem. In addition, several research groups found an increase in mycorrhizal short roots and extra-radical mycelium in response to elevated CO_2 (Ineichen et al., 1995; Lewis & Strain, 1996; Runion et al., 1997; Walker et al., 1997; Wiemken et al., 2001).

Microbial biomass nitrogen

Understanding the effects of elevated CO_2 on microbial biomass N is of great importance, as such N plays a key role in plant productivity in N limited ecosystems (Diaz et al., 1993; Zak et al., 1993). Elevated CO_2 can have a positive effect (Diaz et al., 1993; Zak et al., 1993; Niklaus, 1998) or no effect (Berntson & Bazzaz, 1998; Niklaus, 1998; Zak et al., 2000b) on soil microbial N. For example, Niklaus (1998) reported that microbial biomass N was increased by 18%, although microbial biomass C was not influenced by elevated CO_2. In tallgrass prairie exposed to elevated CO_2 for 8 years, soil microbial biomass N tended to be greater under elevated CO_2 compared to ambient treatment (Williams et al. 2000). Billings et al. (2004) studies on the effects of elevated CO_2 on soil N dynamics in the Mojave Desert showed increased microbial biomass N in dry soils under a perennial grass. However, Barnard et al. (2004) showed that microbial biomass N was not affected by elevated CO_2 in four European grassland ecosystems after several years of treatment.

Microbial population and respiration

O'Neill et al. (1987) and Whipps (1985) were unable to find differences in the total number of bacteria between ambient and elevated CO_2 treatments. In studies of nitrifiers, the elevated CO_2 had no effect on population of nitrifiers (O'Neill et al., 1987; Schortemeyer et al., 1996). However, several authors have observed an increase in bacterial numbers under elevated CO_2 (Rogers et al., 1992, Runion et al., 1994; Insam et al., 1999; Marilley et al., 1999). In addition, Schortemeyer et al. (1996) showed that number of specific species increased two fold in a natural Florida scrub ecosystem after 2 years of CO_2 enrichment while no effect was found for total population.

Soil respiration is measured as the flux of CO_2 from the soil, and it integrates both autotrophic and heterotrophic sources. The CO_2 in autotrophic respiration comes from the respiration of roots and associated mycorrhizae; its rate is closely linked to current photosynthesis, but root carbohydrate reserves also contribute. The CO_2 in heterotrophic respiration comes from the metabolism of rhizodeposited compounds from living roots and the metabolism of plant litter and soil organic matter by soil fauna and microorganisms. Many studies have found that microbial respiration was significantly greater in elevated CO_2 conditions (Rogers et al., 1992; O'Neill, 1994; Runion et al., 1994; Dhillion et al., 1996; Williams et al., 2000). Williams et al. (2000) observed that microbial respiration was higher in tall grass prairie exposed to elevated CO_2 for 8 years. However, Tuchman et al. (2003) reported microbial community respiration decreased significantly by 36.8% in the stream ecosystems with *Populus tremuloides* seedling grown in elevated CO_2 conditions.

Nitrification and denitrification

Understanding of the effects of elevated CO_2 on processes such as nitrification and denitrification is of great concern because these processes regulate soil inorganic N concentrations, nitrate (NO_3^-) leaching and production of nitrous oxide (N_2O). The effects of CO_2 on denitrification has attracted particular attention because it is one of the most important mechanisms returning N from terrestrial or aquatic ecosystems to the atmosphere (Kaplan et al., 1979), while also mediating release of the potent greenhouse gas N_2O (Smart et al., 1997; Baggs et al., 2003; Deiglmayr et al., 2004). It has been reported that denitrifying activity increased significantly under CO_2 enrichment in both controlled environments and field conditions. For example, Ineson et al. (1998) found higher N_2O-N, metabolite of denitrification, and production beneath *Loliumperenne* growing under high N inputs and elevated CO_2. The higher denitrification rates under elevated CO_2 may be due to activation of denitrifiers by higher growth of fine roots and enhanced root exudation (Rogers et al., 1992) and formation of anaerobic conditions induced by increased soil respiration and soil water content (Korner, 2000; Zak et al., 2000b).

However, several researchers have reported that elevated CO_2 did not affect denitrifying enzymes activity (DEA) and nitrifying enzyme activity (NEA) (Barnard et al., 2004), or alternatively decreased them (Matamala and Drake, 1999). Even in a single study, contrasting responses have been observed depending on sampling dates (Billings et al., 2003). Zak et al. (2000) found that nitrification did not change in bulk soils under elevated CO_2 after 2.5 growing seasons. Barnard et al. (2004) showed that elevated CO_2 had limited effects on the amount of active nitrifying and denitrifying enzymes presented in four European grassland soils. In mono-specific grassland mesocosms (*Holcuslanatus* and *Festucarubra*) grown under elevated CO_2, NEA decreased substantially, while DEA was less responsive to elevated CO_2 (Barnard et al., 2004).

Methanogenesis

The concentration of atmospheric methane (CH_4) has increased at the rate 1% per year. Most of the atmospheric CH_4 is produced by bacterial activities in extremely anaerobic ecosystems such as natural and cultivated wetlands, sediment, sewage, landfills, and the rumen of herbivorous animals. In recent years, a number of studies have addressed the potential changes in trace gas emissions from wetlands exposed to elevated CO_2. For example, Drake (1992) reported CO_2 enrichment stimulated CH_4 emissions by 80% in a salt marsh containing sedge *S. olneyi*. Hutchin et al. (1995) also found a similar effect for mire peat and vegetation exposed CO_2 enrichment treatment. Megonigal and Schlesinger (1997) who performed experiments with *Orontium aquaticum* reported CH_4 emissions increased by 136% under elevated CO_2. However, Kang et al. (2001) found no significant differences for CH_4 emission on northern fen peat with *Juncus* and *Festuca* spp., although the mean value was higher under elevated CO_2 conditions. Saarnio et al. (2000) found that elevated CO_2 (560 ppm) increased CH_4 efflux by only 15- 20% in boreal mires over two years using mini-FACE rings. The increase was clearly weaker than that in previous reports from temperate or subtropical areas where CH_4 efflux increased by 80-150% during the growing season (Dacey et al., 1994; Hutchin et al., 1995, Megonigal & Schlesinger, 1997). The increases in CH_4 emission under elevated CO_2 conditions can be explained by two mechanisms. First, elevated CO_2 often results in ample supply of carbon into soil and hence larger amounts of organic carbon are available for methanogens. Secondly, elevated CO_2 concentration might indirectly enhance CH_4 emissions from wetlands by promoting net primary production. Previous studies of natural and artificial wetlands have reported positive correlations between CH_4 emission rates and plant aboveground biomass. However, a few studies have reported the opposite trend with CO_2 enrichment leading to the attenuation of CH_4 production due to increased delivery of oxygen to the rhizosphere. For example, Schrope et al. (1999) reported CH_4 emissions from rice grown in a sandy soil under doubled CO_2 were 4 times less. The increased root biomass due to elevated CO_2 may have more effectively aerated the soil, suppressing CH_4 production. Uncertainties in the response of CH_4 emission from wetlands exposed to elevated CO_2 arise due to a lack of long term studies. In addition, changes in litter chemistry, nutrient deficiency, the height of water table or peat lands area may also interfere with the capacity for CH_4 emissions from wetland ecosystems under elevated CO_2 conditions.

Soil enzyme activities

Alterations in microbial mineralization and nutrient cycling may control the long term response of ecosystem to elevated CO_2. Because microorganisms are regulators of decomposition, an understanding of microbial activity is crucial. Elevated CO_2 concentration can affect extracellular enzyme activities in several ways. Dhillion et al. (1996) reported that dehydrogenase, cellulose, phosphatase, and xylanase were increased by elevated CO_2 in the root region of soil from monocultures of *Bromusmadritensis*, a common and sometimes dominant annual grass in Mediterranean model ecosystem. Of the four enzymes examined, dehydrogenase and xylanase activities were significantly higher in soils under elevated CO_2 than in ambient. Moorhead & Linkins (1997) suggested that elevated CO_2 altered the soil enzyme characteristics in a tussock tundra ecosystem. They found significantly higher phosphatase activities at 680 mol mol^{-1} CO_2 on the surfaces of plant roots, mycorrhizal surfaces, and in the shallowest organic horizons soil.

Several studies have assessed CO_2 effects on enzyme involved in nitrogen fixation. An increase in symbiotic nitrogen fixation activity for *T. repens* growth under enriched CO_2 atmosphere. Elevated CO_2 stimulated greater N_2 fixation and nitrogenase activity in stands of the C_3 sedge, rice, *Scirpusolneyi* and also in plant free marsh sediment.

Microbial community composition

Although changes in soil microbial number, biomass, activity, and microbial C and N in response to elevated CO_2 have been demonstrated in several studies information on the effects on soil microbial community structure is highly limited. For microbial community structure, phospholipid fatty acid analysis and several molecular methods have been employed. For example, fungal community composition has been determined by terminal-restriction fragment length polymorphism (TRFLP) analysis of the internal transcribed spacer (ITS) region (Klamer et al., 2002). In addition, DNA hybridization, percent G+C base profiling, and PCR-based fingerprinting were used in other studies. Marilley et al. (1999) employed DNA restriction analysis (ARDRA) and colony hybridization, while PCR-RFLP with primers for the *narG* gene was used by Deiglmayr et al. (2004). Several studies have suggested that elevated atmospheric CO_2 could alter the composition of soil microbial communities due to changes in the amount and or composition of plant material input into the soil. Bacterial substrate utilization assay showed that components or assemblages of bacterial communities might be susceptible to shifts or change by elevated CO_2 in root region soil from monocultures of *Bromusmadritensis*.

PCR fingerprinting of genomic DNA by Montealegre et al. (2002) showed that the isolates (*Rhizobium* strains) from plants grown under elevated CO_2 were genetically different from those isolates obtained from plants grown under ambient conditions in a pasture ecosystem. These results indicate that elevated atmospheric CO_2 may shift community composition of soil microorganisms. In addition, elevated atmospheric CO_2 affects the competitive ability of root nodule symbionts, most likely leading to a selection of these particular strains to nodulate white clover probably occurring after 3 years of CO_2 fumigation. Specific species responds significantly to changes in CO_2 concentration. However, some studies have shown no alteration of microbial community composition by elevated CO_2 concentrations. Zak et al. (1996) did not find any significant changes in microbial community composition in soil. Ringelberg et al. (1997) reported that elevated CO_2 caused only subtle changes in gram negative bacteria and actinomycetes. Griffiths et al. (1998), using broad-scale DNA techniques, showed that the rhizosphere microbial communities of ryegrass and wheat (*Triticumaestivum* L.) were 86% similar under ambient and elevated CO_2.

Conclusions

The overall mechanisms and responses of soil microorganisms to elevated CO_2 are summarized in Fig. 1. Soil microorganisms are known to be affected by elevated CO_2 through various interactions with plants, including increased root exudation, altered leaf chemistry, and competition for resources. As microbial responses to elevated CO_2 are indirectly mediated by plant responses, results of studies considering CO_2 effects on microorganisms are often relatively unclear. Higher C supply from plants caused by elevated CO_2 may enhance certain microbial processes such as CH_4 emission from rice paddies and wetlands. However, other microbial properties such as extracellular enzyme activities and microbial community structure are connected partially with other factors (e.g., nutrient availability, vegetation type, or microhabitat), and hence unequivocal conclusions about the effects of elevated CO_2 on soil microorganisms particularly in rice are still lacking. An improved understanding of microbial responses to elevated CO_2 could be obtained in further studies. Techniques such as micro-arrays and other molecular tools could be applied more effectively to this field. Compared to other fields of microbiology, information gathering using this approach is relatively lacking. Secondly, better experimental design and sampling techniques appear warranted if we are to account for interferences from other factors as well as artifacts from heterogeneity of soil media. Thirdly, there are likely to be many advantages to be gained from the simultaneous application of multiple techniques to a single or small set of experiments, so that various aspects of microbial structure and functions (and their interactions) can be considered. Finally, appropriate statistical techniques and modeling approaches are required to extrapolate microbial data to ecosystem or global scales.

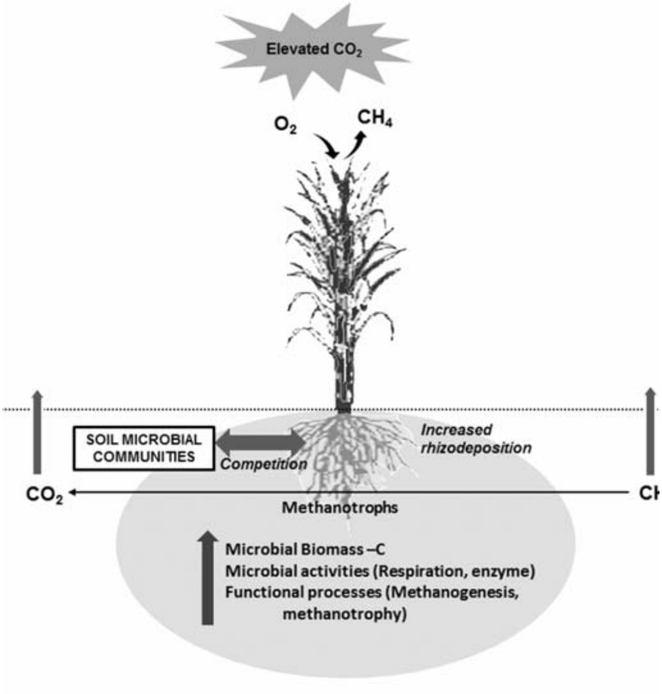


FIGURE 1. *Soil microbial processes pertaining to carbon dynamics in paddy system affected by elevated carbon dioxide in the atmosphere*

References

Baggs, E.M., Richter, M., Cadisch, G., & Hartwig, U.A. (2003). Denitrification in grass swards is increased under elevated atmospheric CO_2. *Soil Biology and Biochemistry*, 35, 729-732.

Barnard, R., Barthes, L., Le Roux, X., Harmens, H., Raschi, A., Soussana, J.F., Winkler, B., & Leadley, P.W. (2004). Atmospheric CO_2 elevation has little effect on nitrifying and denitrifying enzyme activity in four European grasslands. *Global Change Biology*, 10, 488-497.

Berntson, G.M. & Bazzaz, F.A. (1998). Regenerating temperate forest mesocosms in elevated CO2: belowground growth and nitrogen cycling. *Oecologia*, 113, 115-125.

Berntson, G.M., and Bazzaz, F.A. (1996). Belowground positive and negative feedbacks on CO_2 growth enhancement. *Plant and Soil*, 187, 119–131.

Billings, S.A, Schaeffer, S.M., Zitzer, S., & Evans, R.D. (2003). Trace N gas losses and N mineralization in an intact Mojave Desert ecosystem with elevated CO_2. *Soil Biology and Biochemistry,* 34, 1777-1784.

Billings, S.A., Schaeffer, S.M, & Evans, R.D. (2004). Soil microbial activity and N availability with elevated CO_2 in Mojave desert soils. *Global Biogeochemical Cycles,* 18, GB1011.

Dacey, V.W.H., Drake, B.G. & Klug, M.J. (1994). Stimulation of methane emission by carbon dioxide enrichment of marsh vegetation. *Nature,* 370, 47-49.

Deiglmayr, K., Philippot, L., Hartwig, U.A., & Kandeler, E. (2004). Structure and activity of the nitrate-reducing community in the rhizosphere of *Loliumperenne*and *Trifoliumrepens*under long-term elevated atmospheric p CO_2. *FEMS Microbiology and Ecology*, 49, 445-454.

Dhillion, S.S., Roy, J., & Abrams, M. (1996). Assessing the impact of elevated CO_2 on soil microbial activity in a Mediterranean model ecosystem. *Plant and Soil,* 187, 333-342.

Diaz, S., Grime, J.P., Harris, J., & McPherson, E. (1993). Evidence of a feedback mechanism limiting plant response to elevated carbon dioxide. *Nature,* 364, 616-617.

Drake, B.G. (1992). A field study of the effects of elevated CO_2 on ecosystem processes in a Chesapeake Bay wetland. *Australian Journal of Botany,* 40, 579-595.

Griffiths, B.S., Ritz, K., Ebblewhite, N., Paterson, E., & Killham, K. (1998). Ryegrass rhizosphere microbial community structure under elevated carbon dioxide concentrations, with observations on wheat rhizosphere. *Soil Biology and Biochemistry*, 30, 315-321.

Hoosbeek, M.R., Li, Y., & ScarasciaMugnozza, G. (2006). Free atmospheric CO_2enrichment (FACE) increased labile and total carbon in the mineral soil of a short rotation Poplar plantation. *Plant and Soil,* 281, 247–254.

Hungate, B.A., Jaeger III, C.H., Gamara, G., Chapin II, S.F., & Field, C.B. (2000). Soil microbiota in two annual grasslands: Responses to elevated atmospheric CO_2. *Oecologia,* 124, 589-598.

Hutchin, P.R., Press, M.C., Lee, J.A., & Ashenden, T.W. (1995). Elevated concentrations of CO_2 may double methane emissions from mires. *Global Change Biology*, 1, 25-128.

Ineichen, K., Wiemken, V., & Wiemken, A. (1995). Shoots, roots and ectomycorrhizal formation of pine seedlings at elevated atmospheric carbon dioxide. *Plant Cell and Environment*, 18, 703-707.

Ineson, P., Coward, P.A., & Hartwig, U.A. (1998). Soil gas fluxes of N2O, CH4 and CO2 beneath *Loliumperenne*under elevated CO_2: The Swiss free air carbon dioxide enrichment experiment. *Plant and Soil, 198*, 89-95.

Insam, H., Baath, E., Berreck, M., Frostegard, A., Gerzabek, M.H., Kraft, A., Schinner, F., Schweiger, P., & Tschuggnall, G. (1999). Responses of the soil microbiota to elevated CO_2 in an artificial tropical ecosystem. *Journal of Microbiologiacal Methods,* 36, 45-54.

IPCC. (2007).Climate Change 2007- the Physical Science Basis. Working Group I Contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press, Cambridge, UK, pp. 1009.

Jones, T.H., Thompson, L.J., Lawton, J.H., Bezemer, T.M., Bardgett, T., Blackburn, T.M., Bruce, K.D., Cannon, P.F., Hall, G.S., Jones, C.G., Kampichler, C., Kandeler, E., & Richie, D.A. (1998). Impacts of rising atmospheric CO_2 on soil biota and processes in model terrestrial ecosystems. *Science,* 280, 411-413.

Kampichler, C., Kandeler, E., Bardgett, R.D., Jones, T.H., & Thompson, L.J. (1998). Impact of elevated CO_2 concentration on soil microbial biomass and activity in a complex, weedy field model ecosystem. *Climate Change Biology*, 4, 335-346.

Kang, H.J., Freeman, C., & Ashendon T.W., (2001). Effects of elevated CO_2 on fen peat biogeochemistry. *Science of the Total Environment*, 279, 45-50.

Kaplan, W., Valiela, I., & Teal, J.M. (1979). Denitrification in a salt marsh ecosystem. *Limnology and Oceanography*, 24, 726-734.

Keeling, C.D., & Whorf, T.P. (1998). Atmospheric CO_2concentrations — Mauna Loa Observatory, Hawaii, 1958-1997 (revised August 2000). NDP-001.Carbon dioxide information analysis center, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Klamer, M., Roberts, M.S., Levine, L.H., Drake, B.G., & Garland, J.L. (2002). Influence of elevated CO_2 on the fungal community in a Coastal scrub oak forest soil investigated with terminal restriction fragment length polymorphism analysis. *Applied and Environmental Microbiology,* 68, 4370-4376.

Korner, C. (2000). Biosphere responses to CO_2 enrichment. *Ecological Applications,* 10, 1590-1619.

Larson, J.L., Zak, D.R., & Sinsabaugh, R.L. (2002). Extracellular enzyme activity beneath temperature trees growing under elevated carbon dioxide and ozone. *Soil Science Society of American Journal,* 66, 1848- 1856.

Lewis, J.D. & Strain, B.R. (1996). The role of mycorrhizas in the response of *Pinustaeda*seedlings to elevated CO_2. *New Phytologist,* 133, 431-443.

Marilley, L., Hartwig, U.A., & Aragno, M. (1999). Influence of an elevated atmospheric CO_2 content on soil and rhizosphere bacterial communities beneath *Loliumperenne*and *Trifoliumrepens*under field conditions. *Microbial Ecology, 38*, 39-49.

Matamala, R., & Drake, B.G. (1999). The influence of atmospheric CO_2 enrichment on plant-soil nitrogen interactions in a wetland plant community on the Chesapeake Bay. *Plant and Soil,* 210, 93-101.

Megonigal, J.P. & Schlesinger, W.H. (1997). Enhanced CH_4 emissions from a wetland soil exposed to elevated CO_2. *Biogeochemistry, 37*, 77-88.

Mitchell, E.A.D., Gilbert, D., Buttler, A., Amblard, C., Grosbernier, P., & Gobat, J.M. (2003). Structure of microbial communities in *Sphagnum* peatlands and effect of atmospheric carbon dioxide enrichment. *Microbial Ecology*, 46, 187-199.

Montealegre, C.M., van Kessel, C., Russelle, M.P., & Sadowsky, M.J. (2002). Changes in microbial activity and composition in a pasture ecosystem exposed to elevated atmospheric carbon dioxide. *Plant and Soil, 243*, 197-207.

Moorhead, D.L. & Linkins, A.E. (1997). Elevated CO_2 alters belowground exoenzyme activities in tussock tundra. *Plant and Soil,* 189, 321-329.

Niklaus, P.A. (1998). Effects of elevated atmospheric CO_2 on soil microbiota in calcareous grassland. *Global Change Biology*, 4,451-458.

Niklaus, P.A., Kandeler, E., Leadley, P.W., Schmid, B., Tscherko, D., & Korner, C. (2001). A functional link between plant diversity, elevated CO_2 and soil nitrate. *Oecologia,* 127, 540-548.

O'Neill, E. (1994). Responses of soil biota to elevated atmospheric carbon dioxide. *Plant and Soil,* 165, 55-65.

O'Neill, E.G., Luxmoore, R.J., & Norby, R.J. (1987). Elevated atmospheric CO_2 effects on seedling growth, nutrient uptake, and rhizosphere bacterial populations of *Liriodendron tulipifera*L. *Plant and Soil, 104*, 3-11.

Pregitzer, K.S., Zak, D.R. Maziasz, J., DeForest, J., Curtis, P.S., & Lussenhop, J. (2000). Interactive effects of atmospheric CO_2 and soil-N availability on fine roots of *Populustremuloides*. *Ecoogical Applications, 10*, 18-13.

Ringelberg, D.B., Stair, J.O., Alameida, J.S., Norby, R.J., O'Neill, E.G., & White, E.C. (1997). Consequences of rising atmospheric carbon dioxide levels for the belowground microbiota associated with white oak. *Journal of Environmental Quality,* 26, 409-503.

Rogers, H.H., Prior, S.A., & ONeill, E.G. (1992). Cotton root and rhizosphere responses to free-air CO_2 enrichment. *Critical Reviews in Plant Sciences,* 11, 251-263.

Runion, G.B., Curl, E.A., Rogers, H.H., Backman, P.A., Rodriguez-Kabana, R., & Helms, B.E. (1994). Effects of free-air CO_2 enrichment on microbial on microbial populations in the rhizosphere and phyllosphere of cotton. *Agricultural and Forest Meteorology,* 70, 117-130.

Runion, G.B., Mitchell, R.J., Rogers, H.H., Prior, S.A., & Counts, T.K. (1997). Effects of nitrogen and water limitation and elevated atmospheric CO_2 on ectomycorrhiza of longleaf pine. *New Phytologist,* 137, 681-689.

Saarnio, S., Saarinen, T., Vasander, H., & Silvola, J. (2000). A moderate increase in the annual CH_4 efflux by raised CO_2 or NH_4NO_3 supply in a boreal oligotrophic mire. *Global Change Biology,* 6, 137-144.

Schortemeyer, M., Dijkstra, P., Johnson, D.W., & Drake, B.G. (2000). Effects of elevated atmospheric CO_2 concentration on C and N pools and rhizosphere processes in a Florida scrub oak community. *Global Change Biology,* 6, 383-391.

Schortemeyer, M., Hartwig, U.A., Hendrey, G.R., & Sadowsky, M.J. (1996). Microbial community changes in the rhizospheres of white clover and perennial ryegrass exposed to free air carbon dioxide enrichment (FACE). *Soil Biology and Biochemistry,* 28, 1717-1724.

Schrope, M.K., Chanton, J.P., Allen, L.H., & Baker, J.T. (1999). Effect of CO_2 enrichment and elevated temperature on methane emissions from rice, *Oryza sativa*. *Global Change Biology*, 5, 587-599.

Smart, D.R., Ritchie, K., Stark, J.M., & Bugbee, B. (1997). Evidence that elevated CO_2 levels can indirectly increase rhizosphere denitri.er activity. *Applied and Environmental Microbiology,* 63, 4621-4624.

Tuchman, N.C., Wahtera, K.A., Wetzel, R.G., & Teeri, J.A. (2003). Elevated atmospheric CO_2 alters leaf litter nutritional quality for stream ecosystems: An *in situ* leaf decomposition study. *Hydrobiologia,* 495, 203-211.

Walker, R.F., Geisinger, D.R., Johnson, D.W., & Ball, J.T. (1997). Elevated atmospheric CO_2 and soil N fertility effects on growth, mycorrhizal colonization, and xylem water potential of juvenile ponderosa pine in a field soil. *Plant and Soil,* 195, 25-36.

Whipps, J.M. (1985). Effects of CO_2 -concentrations on growth, carbon distribution and loss of carbon from the roots of maize. *Journal of Experimental Botany,* 36, 645-651.

Wiemken, V., Laczko, E., Ineichen, K., & Boller, T. (2001). Effects of elevated carbon dioxide and nitrogen fertilization on mycorrhizal fine roots and the soil microbial community in Beech- Spruce eco-systems on siliceous and calcareous soil. *Microbial Ecology,* 42, 126-135.

Williams, M.A., Rice, C.W., & Owensby, C.E. (2000). Carbon dynamics and microbial activity in tall grass prairie exposed to elevated CO_2 for 8 years. *Plant and Soil,* 227, 127-137.

Zak, D.R., Ringelberg, D.B., Pregitzer, K.S., Randlett, D.L., White, D.C., & Curtis, P.S. (1996). Soil microbial communities beneath *Populusgranddentata* grown under elevated atmospheric CO_2. *Ecological Appications,* 6, 57-262.

Zak, D.R., Pregitzer, K.S., King, J.S., & Holmes, W.E. (2000a). Elevated atmospheric CO_2, fine roots and the response of soil microorganisms: A review and hypothesis. *New Phytologist,* 147, 201-222.

Zak, D.R., Pregitzer, K.S., Curtis, P.S., & Holmes, W.E. (2000b). Atmospheric CO_2 and the composition and function of soil microbial communities. *Ecological Applications,* 10, 47–59.

Zak, D.R., Pregitzer, K.S., Curtis, P.S., Teeri, J.A., Fogel, R., & Randlett, D.L. (1993). Elevated atmospheric CO_2 and feedback between carbon and nitrogen cycles. *Plant and Soil,* 151, 105-117.

*****

Chapter 8

Climate change feedback and temperature sensitivity of soil organic carbon and its degradation kinetics

P. Bhattacharyya[1*], M.C. Manna[2], K.S.Roy[1], S. Neogi[1] and Mohammad Shahid[1]
[1] Central Rice Research Institute, Cuttack, Odisha, India
[2]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[*]e-mail: pratap162001@yahoo.co.in

Terrestrial ecosystems can release or absorb globally relevant greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), they emit aerosols and aerosol precursors, and they control exchanges of energy, water and momentum between the atmosphere and the land surface. Ecosystems themselves are subject to local climatic conditions, implying a multitude of climate- ecosystem feedbacks that might amplify or dampen regional or global climate change. Of these feedbacks, that between the carbon cycle and climate has recently received much attention. Large quantities of carbon are stored in living vegetation and soil organic matter, and liberation of this carbon into the atmosphere as CO_2 or CH_4 would have a serious impact on global climate. By definition, the carbon balance of an ecosystem at any point in time is the difference between its carbon gains and losses. Terrestrial ecosystems gain carbon through photosynthesis and lose it primarily as CO_2 through respiration in autotrophs (plants and photosynthetic bacteria) and heterotrophs (fungi, animals and some bacteria), although losses of carbon as volatile organic compounds, CH_4 or dissolved carbon (that is, non-CO_2 losses) could also be significant. Quantifying and predicting these carbon-cycle-climate feedbacks is difficult, however, because of the limited understanding of the processes by which carbon and associated nutrients are transformed or recycled within ecosystems, in particular within soils, and exchanged with the overlying atmosphere.

Carbon dynamics

In carbon-cycle-climate models, the effect of the prevailing climate on the carbon balance in terrestrial ecosystems is described mostly by relatively simple response functions and kinetic concepts of CO_2 uptake by photosynthesis and loss by respiration. The fundamental paradigm adopted by researchers over the past two decades has been that photosynthetic uptake is simulated both by increasing CO_2 and, in boreal and temperate regions, by rising temperature, although both effects are expected to saturate at high levels of these variables. On the other hand, the biological processes underlying respiration are assumed to respond to temperature in an exponential way but are not affected by the CO_2 concentration. This leads to the conclusion that the biosphere is able to provide negative feedback to rising CO_2 and temperature until the temperature climbs so high that the stimulating effect on respiration exceeds the CO_2 fertilization effect. Although this conceptual model has provided valuable guidance for experimental and model design, evidence has accumulated in recent years that above- and below-ground processes are intimately linked, constituting a complex and dynamic system with non-negligible interactions. Hence, the situation is much more complicated than previously thought and might result in unexpected dynamics through interactions between physical, chemical and biological processes within the ecosystem- particularly in the soil. This implies that, beyond rising CO_2

levels and rising temperature, other climatic and environmental factors might modify, or even dominate, the carbon balance of the world's ecosystems. Furthermore, not only the long-term rate of change of mean values of parameters such as temperature but also alteration in their variability, including greater extremes, may be crucial to ecosystem carbon dynamics.

Climate changes feedbacks and soil organic carbon dynamics

Climate changes have both direct and indirect effects on the soil organic carbon (SOC) dynamics and its decomposition kinetics as well as microbial activities on SOC decomposition that provide a feedback to the gaseous-C concentrations to the atmosphere and contribute to global warming. Direct effects include temperature mediated soil respiration, SOC decomposition leading to gaseous-C emission, changes in precipitation and extreme climatic events. The indirect effects result from climate-driven changes in plant productivity and diversity that would alter soil physico-chemical conditions, the supply of carbon to soil and, structure and activity of microbial communities involved in decomposition processes and carbon release from soil.

As rates of soil respiration are thought to be more sensitive to temperature than primary production, it is predicted that climate will increase the net transfer of carbon from soil to atmosphere, there by creating a positive feedback to climate change. Growing stress tolerance species also contribute to a positive feedback to climate change. Increase of primary production (higher photosynthesis) and reduction of the length of growing season causes negative feedback to climate change by reducing the CO_2 emission to atmosphere and absorbing more CO_2 from atmosphere. The indirect effects which includes positive feed backs are i) percolation and runoff losses of dissolved organic carbon (DOC), ii) higher root exudation that causes faster SOC decomposition through "Priming effect" and promote methanogenesis and hence enhance the C losses from soil as CH_4. The indirect negative feedbacks include i) increasing plant-microbial competition for nitrogen (N) that causes ecosystem carbon (C) accumulation, ii) increasing growth of mycorrhizal fungi causing C accumulation and iii) stimulation of microbial biomass and immobilization of soil N causing limitation of N availability to plant and hence accumulation of C in soil . Another indirect effect on climate change (both positive and negative feedbacks) is through shifts in the functional composition and diversity of microbes and vegetation which occurs over longer time scales of decades and centuries.

Factors associated to carbon dynamics and climatic feedbacks

Primary productivity in more than half of the world's ecosystem is substantially limited by the availability of water. Hence, changes in precipitation will have direct effects on ecosystem C dynamics. In a warmer world, evaporation is expected to increase, leading to a more negative water balance, whereas decreased water loss through stomata in a CO_2-richer world will tend to mitigate this effect. The net effect (production minus respiration) of a more negative overall water balance probably depends on the water-holding capacity of the soil, the vertical distribution of C and roots in the soil, and the general drought sensitivity of the vegetation. For instance, if most of the soil C is concentrated at the top of the soil, while roots go deep into a soil with high water-holding capacity, or even tap the groundwater, soil carbon decomposition will initially be more strongly affected by drought than will vegetation productivity, as the topsoil dries out first. Water limitation may even suppress the effective ecosystem-level response of temperature on respiration. Conversely, if soil water-holding capacity is low, as in shallow soils, vegetation productivity will be strongly affected by a negative water balance. Hence, under drier conditions, there are predictions of increased sequestration by suppression of respiration and net loss of C through decreased productivity.

A second important interacting factor is the available N, which often determines the magnitude of the CO_2 fertilization effect and may suppress it completely if N is limiting. There are also indications of strong interactions between water and N, with N becoming more limiting under drier conditions. Other factors to be considered are changes in the amount and quality (direct or diffuse) of light, which can alter vegetation productivity, and increases in air pollutants and ozone, with their detrimental effects on primary production.

Feedbacks in the carbon-cycle-climate system

As discussed above, the net effect of any environmental change on the carbon balance in an ecosystem depends on the reactions of both photosynthesis and respiration; in other words, on above-ground and below-ground processes. Below-ground processes in particular are still poorly understood yet provide a number of potentially important feedbacks in the carbon-cycle-climate system.

Current estimates of carbon stored deep-frozen in permafrost regions amount to at least 400 petagrams (4×10^{11} tonnes) of carbon that is relatively unprocessed and labile as the frozen state protects it from microbial decomposition. Moss and turflayers provide very good insulation against the atmosphere. With rising summer temperatures, these soils begin to melt, the carbon becomes metabolized and microbial metabolism may release enough heat (the 'during heap-effect) to facilitate further melting, providing a nonlinear positive-feedback mechanism to enhance permafrost melting and, though CH_4 and CO_2 emissions, to increase the greenhouse effect.

Another mechanism for potential mobilization of large amounts of carbon is the so-called 'microbial priming effect'. It has been shown in several experimental systems that the addition of substrates with readily available energy (for example, glucose and cellulose) to the soil stimulates the decomposition of 'old' soil carbon. Fontaine et al. (2004) showed that simply by adding cellulose to the soil they could mobilize carbon from the subsoil of grasslands that was assumed to be stable, whereas other factors such as temperature, nitrogen addition or increasing oxygen concentration had no effect. Addition of such material even induced a net loss of carbon from the soil samples, as the soil carbon stock is large. In the context of climate change this effect may induce a positive-feedback effect, particularly in grassland soils. Increasing CO_2 concentrations can lead to enhanced below-ground allocation of labile carbon through roots and root exudates, which can enhance microbial activity and foster decomposition of carbon material that has been deemed stable but was in fact not being attacked because microbes were not active. Also, if rooting patterns change, either because of altered precipitation or a part of general vegetation dynamics, carbon input into deeper layers that were not rooted before might induce release of old carbon through this mechanism.

The interaction of the carbon and nitrogen cycles offer a plethora of mechanism that could alter expected ecosystem carbon response to the prevailing trend in climate change. In nitrogen-limited ecosystems, nitrogen nutrition limiting the CO_2 fertilization effect on canopy assimilation is regularly found after a few years of increasing CO_2 levels. There are also indications that nitrogen availability influences the decomposition of soil organic matter. Fungi use lignin, an abundant, stable organic substance found in plant cell walls, as a nitrogen source under conditions of limited nitrogen availability. Enhanced decomposition of lignin may lead to a positive feedback in response to rising atmospheric CO_2. On timescales longer than a few years, however, acclimation or change in species composition, or, for example, increased nitrogen fixation through increased carbohydrate input into the soil, may relax or even overcompensate for the nitrogen-limitation effects. Also, an interaction with microbial 'priming' through more intensive and deeper plant rooting is not unlikely, as a decrease in nitrogen availability often leads to a larger allocation of carbon to roots.

Temperature sensitivity of soil organic carbon

The temperature sensitivity of decomposition of the enormous global stocks of SOC has recently received considerable interest. Interest in this topic is high because of its importance in the global carbon cycle and potential feedbacks to climate change. This recent controversy has focused primarily on organic matter in upland mineral soils. These soils have reasonably good drainage and aeration, allowing roots and soil fauna to penetrate into mineral soil layers, thus mixing SOC with mineral particles. Conditions in upland mineral soils are also favourable for decomposition, resulting in relatively low carbon densities. In contrast, in wetlands and peatlands where anaerobic conditions frequently persist, decomposition proceeds much more slowly, and deep layers of organic matter accumulate on top of mineral layers.

Factors controlling decomposition of organic carbon

The stocks of organic carbon in soils result from the balance between inputs and outputs of carbon within the belowground environment. Inputs are primarily from leaf and root detritus. Outputs are dominated by the efflux of CO_2 from the soil surface, although CH_4 efflux and hydrological leaching of dissolved and particulate carbon compounds can also be important. The production of CO_2 in soils is almost entirely from root respiration and microbial decomposition of organic matter. Like all chemical and biochemical reactions, these processes are temperature dependent. Root respiration and microbial decomposition are also subject to water limitation. Hence, most empirical models relate the efflux of CO_2 from soils (often lumping microbial and root respiration together as 'soil respiration') to temperature and often also to some scalar of soil water content or precipitation. This much is not controversial.

The kinetics of enzymatic reactions in well-mixed media is also not controversial. Activation energies are related to the ambient temperature and to the molecular structure of the organic-C reactant. The temperature sensitivity of decomposition increases with increasing molecular complexity of the substrate. The reaction rates are also modified by substrate concentrations and affinities of the enzymes for the substrates.

Soils contain thousands of different organic-C compounds, each with its own inherent kinetic properties. Not only do plants produce a wide range of carbon substrates, but plant detritus also undergoes transformations by microbial degradation or by abiotic condensation reactions that produce new aromatic structures, larger molecular weights, insolubility, or other molecular architectures that affect the types and efficacies of enzymes that can degrade them. These complex molecular attributes are characterized by low decomposition rates, high activation energies, and inherently high temperature sensitivity. The inherent kinetic properties based on molecular structure and ambient temperature could be called as the 'intrinsic temperature sensitivity' of decomposition.

On the other hand, the enzymes for decomposition may be physically or chemically excluded from many of the organic-C substrates within the heterogeneous soil environment, causing substrate limitation at reaction microsites. The observed response to temperature under these environmental constraints, which we shall call the 'apparent temperature sensitivity', may be much lower than the intrinsic temperature sensitivity of the substrate. Conversely, if a temperature-sensitive process alleviates an environmental constraint to decomposition, then the subsequent increase in substrate availability could result in the apparent temperature sensitivity temporarily exceeding the intrinsic temperature sensitivity of the substrate. The environmental constraints that can temporarily or indefinitely affect apparent temperature sensitivities of decomposition include the physical, chemical protection, drought, flooding, freezing etc.

The intrinsic temperature sensitivity of soil organic carbon decomposition

Arrhenius equation and Michaelis-Menten kinetics

The temperature sensitivity of soil respiration is expressed as the van't Hoff's temperature coefficient Q_{10}, which describes the factor by which the rate increases with a 10°C rise in temperature. The Arrhenius equation Eq. 1 describes changes in relative reaction rates (like decomposition rates) as a function of temperature:

$$k = A \exp(-Ea/(RT)) \qquad \text{..........} (1)$$

where, k is the reaction rate constant; A is the frequency factor; Ea is the required activation energy in joules per mole; R= 8.314 $JK^{-1}mol^{-1}$ gas constant and T is the temperature.

Soil organic matter with complex molecular attributes (e.g. recalcitrant SOM, adsorbed SOM, complexed SOM) is characterized by low decomposition rates, high activation energies and, therefore, an 'inherently' high temperature sensitivity. The activation energy Ea is a constant that is related to an ambient temperature and to molecular attributes of the organic C compound (Davidson & Janssens, 2006). With increasing temperature, there is a declining relative increase in the fraction of molecules with sufficient energy to react, and consequently, the Q_{10} value decreases (Davidson & Janssens, 2006; Tjoelker et al., 2001). This implies highest temperature sensitivities in colder regions where also largest C stocks are found (Post et al., 1982; USDA, 2000). The Arrhenius function also shows that the temperature sensitivity of decomposition increases with increasing stability of organic compounds because stabilized substrates are less reactive due to higher activation energies. This means that the stable pool is more temperature-sensitive than the labile pool, which is characterized by low activation energies.

The application of Arrhenius kinetics is limited under conditions of low substrate availability. As described by Michaelis-Menten kinetics (Eq. 2), the reaction rates are further modified by substrate concentrations [S] and affinities of the enzymes for the substrates Km:

$$k= Vmax * [S] / (Km + [S]) \qquad .... (2)$$

where, k is the reaction rate; Vmax is the maximal rate of enzymatic activity at a given temperature; Km is the Michaelis-Menten constant, representing the affinity of enzymes for the substrates expressed as substrate concentration at which the reaction rate equals Vmax/2 and [S] is the substrate availability (substrate concentration at active site of the enzyme).

Substrate availability is directly affected by stabilisation of organic compounds (e.g. by interaction with mineral surfaces and metal ions, spatial inaccessibility due to aggregation and hydrophobocity (Sollins et al., 1996; von Lutzow et al., 2006)) or indirectly by external control factors (e.g. water, oxygen and nutrient supply, temperature, pH) that restrict decomposition. *In situ* temperature insensitive processes such as seasonal litter fall, drying rewetting and tillage alter the release of easily decomposable substrates.

Canceling effects

When substrate [S] is abundant and larger than Km ([S]>Km) and the temperature does not exceed the optimum temperature, Km becomes insignificant (the term [S]/(Km + [S])) and the temperature response of Vmax determines the decomposition rate, which depends only on the catalytic effect exerted by enzymes according to Arrhenius. However, when substrate availability [S] is low- as in most soils, Km becomes relevant and the decomposition rate depends on the enzyme concentration as well as on the substrate concentration. Because Km and Vmax increase with temperature (Arrhenius, 1889), the temperature sensitivities of Vmax and Km (nominator/denominator in Eq. 2) can nutralise each other (Davidson et al., 2006). This 'cancelling effect' becomes significant when substrate concentration [S] is low and also within the range or lower than Km and if both Km and Vmax have similar temperature sensitivities (Larionova et al., 2007). Results by Gershenson et al. (2009) show that addition of readily available substrates significantly increases Q_{10} values because substrate saturation eliminates the canceling effect of Km on the measured Q_{10} values. When Vmax and Km cancel each other out, respiration is controlled by temperature-sensitive processes that alleviate substrate limitation, e.g. decomposition of stabilized SOC pools is a process that produces available substrate.

As most soils are C-limited (Cheng et al., 1996; Ekschmitt et al., 2005), the cancelling effect can be an important factor controlling the 'actual' temperature sensitivity in soils *in situ*. The cancelling effect is short-lived if the time delay between Vmax and Km changes is significant, whilst synchronous alterations of these parameters lead to the Vmax and Km cancelling each other out in the long term.

Conclusions

The picture of a gradual increase in CO_2 and temperature, with separable, non-interactive effects on assimilation and respiration, needs to be replaced by a multifactor view, by more sophisticated characterization of changes in environmental factors, including their variability and extremes, and, maybe most importantly, by stronger integrative consideration of complex interactions between ecosystem processes at different levels of organization. Most of these emerging characteristics point to a lower CO_2– sequestration potential than estimated by current models and highlight the vulnerability of soil carbon that has accumulated over millennia. A positive feedback of ecosystem carbon to climate change might occur earlier and more strongly than currently predicted in coupled carbon-cycle-climate models.

Both the Arrhenius equation and Michaelis-Menten kinetics demonstrate different temperature sensitivities of differently stabilized SOC pools. In the Arrhenius equation, temperature sensitivity of decomposition increases with increasing stability of organic compounds because stabilized substrates are less reactive due to higher activation energies (e.g., recalcitrant SOC compounds, complexed SOC and adsorbed SOC). Stabilization of SOC by spatial inaccessibility (e.g., occlusion of SOC by aggregation, hydrophobicity) for microbes and enzymes is considered by Michaelis-Menten kinetics.

In most current C turnover models, the reaction of SOM pools on variations in temperature is considered to be equal (Q_{10}= 2 at 30-35°C; Q_{10}= 4-6 at 5-10°C; based on measurements of the CO_2 efflux from short-term laboratory incubations of bulk soils by Kirschbaum (1995)). Handling bulk SOM as one homogeneous pool ignores the variation in relative abundances of differently stabilized SOM pools and the underlying temperature dependencies in decomposition rates. In addition, the use of fixed Q_{10} values in C turnover models describes a potential temperature sensitivity, but not the actual temperature sensitivity, which is modified by cancelling effects *in situ*.

References

Arrhenius, S. (1889). Über die Reaktionsgeschwindigkeit bei der inversion von Rohrzucker durch Säuren. Journal of Physical Chemistry, 4, 226-248.

Cheng, W., Zhang, Q., Coleman, D.C., Carroll, C.R., & Hoffman, C.A. (1996). Is available carbon limiting microbial respiration in the rhizosphere? Soil Biology and Biochemistry, 28, 1283-1288.

Davidson, E.A., & Janssens, I.A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature, 440, 65-173.

Davidson, E.A., Janssens, I.A., & Luo, Y. (2006). On the variability of respiration in terrestrial ecosystems: Moving beyond Q_{10}. Global Change Biology, 12, 154-164.

Ekschmitt, K., Liu, M., Vetter, S., Fox, O., & Wolters, V. (2005). Strategies used by soil biota to overcome soil organic matter stability-Why is dead organic matter left over in the soil?. Geoderma, 128, 167-176.

Fontaine, S., Bardoux, G., Abbadie, L., & Mariotti, A. (2004). Carbon input to soil may decrease soil carbon content. Ecology Letters, 7, 314-320.

Gershenson, A., Bader, N.E., & Cheng, W.X. (2009). Effects of substrate availability on the temperature sensitivity of soil organic matter decomposition. Global Change Biology, 15, 176-183.

Kirschbaum, M.U.F. (1995). The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic carbon storage. Soil Biology and Biochemistry, 27, 753-760.

Larionova, A.A., Yevdokimov, I.V., & Bykhotevs, S.S. (2007). Temperature response of soil respiration is dependent on concentration of readily decomposable C. Biogeosciences, 4, 1073-1081.

Post, W.M., Emanuel, W.R., Zinke, P.J., & Stagenberger, A.L. (1982). Soil carbon pools and world life zones. Nature, 298, 156-159.

Sollins, P., Homann, P., & Caldwell, B.A. (1996). Stabilization and destabilization of soil organic matter: Mechanisms and controls. Geoderma, 74, 65-105.

Tjoelker, M.G., Oleksyn, J., & Reich, P.B. (2001). Modelling respiration of vegetation: Evidence for a general temperature-dependent Q_{10}. Global Change Biology, 7, 223-230.

USDA. (2000). Soil organic carbon map. Washington, DC: US Department of Agriculture, Natural Resources, Conservation Service, Soil Survey Division, World Soil Resources. Available via DIALOG. http://soil.usda.gov/use/worldsoils/mapindex/order.html.

Von Lützow, M., Kögel-Knabber, I., Ludwig, B., Matzner, E., Ekschmitt, K., Guggenberger, G., Marschner, B., & Flessa, H. (2006). Stabilization of organic matter in temperate soils: Mechanisms and their relevance under different soil conditions-a review. European Journal of Soil Science, 57, 426-445.

*****

Chapter 9

Agro-climatic analysis for understanding climate change and variability

R. Raja*, B.B. Panda and A.K. Nayak
Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: rajatnau@gmail.com

Agriculture will face significant challenges in the 21st century, largely due to the need to increase global food supply under the declining availability of soil and water resources and increasing threats from climate change. There is concern about the impacts of climate change and its variability on agricultural production worldwide. Current research confirms that, while crops would respond positively to elevated carbon dioxide (CO_2) in the absence of climate change, the associated impacts of high temperatures, altered patterns of precipitation, and possibly increased frequency of extreme events, such as drought and floods, will likely combine to depress yields and increase production risks in many parts of the world. In nutshell, climate change introduces new dynamics and uncertainties into agricultural production and considerable uncertainty remains about the intensity, duration, magnitude and location of impacts. Hence, visualizing and anticipating the processes and impacts of climate change on agricultural production systems are very important for making appropriate policy decisions. Combinations of general circulation models, regional circulation models, crop models, soil models, agro-ecological system models, and economic models are being used to illustrate potential impacts of climate change in the coming decades based on various climate scenarios (Olson et al., 2008; Hein et al., 2009; Thornton et al., 2010). In addition to the global/ regional models, agro-climatic analysis of a particular region can help in understanding the climatic characteristics and crop performance of the region and also to know the impact of climatic variability on its agriculture. This will facilitate thorough understanding of the climatic conditions, determining the suitable agricultural management practices for taking advantage of the favorable weather condition and avoiding or minimizing risks due to adverse weather conditions. This chapter deals with various models and methods of agro-climatic analysis which will help in understanding the climatic conditions of a region and in turn help in determining the suitable agricultural management practices to tide over the possible negative effects of climate change/ variability.

Global circulation models

The climate system is global. Observations, theory, and models are all needed in climate research. Comprehensive climate models are based on physical laws and allow for numerical simulations. The climate system is characterized by a broad range of spatial scales and time scales. Consequently, Global circulation models (GCMs) can effectively address large-scale climate features such as the general circulation of the atmosphere and the ocean, and sub-continental patterns of, for example, temperature and precipitation (Rummukainen, 2010). Climate models have been demonstrated to reproduce observed features of recent climate and past climate changes. There is considerable confidence that GCMs provide credible quantitative estimates of future climate change, particularly at continental and larger scales (Randall et al., 2007). Confidence in these estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation).

Regional circulation models

The resolution (grid scale) of GCMs is at best around 100–200 km (Meehl et al., 2007). Their real resolution is more like 6–8 grid distances, i.e., of the order of 1000 km (Grotch & MacCracken, 1991). This falls short of many key regional and local climate aspects, e.g. intensive precipitation. Very high global model resolution would of course give rise to simulation of regional and local aspects (Mizuta et al., 2006). Global circulation models of this kind are, however, still not feasible due to their high computational cost.

Hence, Regional circulation models (RCMs) were developed with the concept of 'downscaling'. Its purpose is to obtain regional or local detail from either sparse observations or low resolution numerical simulations. Regional models are sometimes called comprehensive, consistent, and physically based interpolator or, in more popular terms, a magnifying glass. This does not imply that RCMs are simple. Their description of climate processes is as complex as in comprehensive GCMs. Downscaling can in principle be applied to refine any data, regardless of its resolution. The two main downscaling methods are known as statistical and dynamical downscaling. The former involves finding robust statistical relationships between large scale climate variables (e.g., the mean sea level pressure field) and local ones (such as temperature or precipitation). There is a wealth of specific methods for this (Christensen et al., 2007). As already has been alluded to, dynamical downscaling by means of RCMs (Christensen et al., 2007) relies on the same physical–dynamical description of fundamental climate processes that is at the core of GCMs. There are two further approaches to dynamical downscaling. One of these is to use a high resolution atmospheric global model (Christensen et al., 2007). Another technique is a global model with a variable-resolution grid (Fox-Rabinovitz et al., 2008; Lal et al., 2008). In this case, the computational grid is made dense over the region of interest, but left sparser elsewhere. These two approaches have their own strengths and weaknesses.

The primary assumption in regional modeling is that data on the climate; large-scale information is used to force an RCM over a limited area. Such a regional domain, as compared to a global one, allows for high resolution without a prohibitive increase in computational cost. Driving data are supplied to the regional model as lateral (and often also sea surface) boundary conditions. The basic set of boundary conditions contains temperature, moisture, and circulation (winds), as well as sea surface temperature and sea ice. An accurate treatment of boundary conditions is a central issue in regional modeling.

The Inter-governmental Panel on Climate Change (IPCC) has projected the following changes in climate with respect to South Asian region (Christensen et al., 2007) as a whole using GCMs/ RCMs:

Temperature

For the A_1B scenario (which assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies with balanced use of fossil and non-fossil energy resources), the MMD (multi-model data set) - A_1B models show a median increase of 3.3°C in annual mean temperature by the end of the 21st century. The median warming varies seasonally from 2.7°C in JJA (June, July, August) to 3.6°C in DJF (December, January, February), and is likely to increase northward in the area, particularly in winter, and from sea to land. Studies based on earlier Atmosphere-Ocean general circulation models (AOGCM) simulations support this picture. The tendency of the warming to be more pronounced in winter is also a conspicuous feature of the observed temperature trends over India. Downscaled projections using the Hadley centre regional model (HadRM2) indicate future increases in extreme daily maximum and minimum temperatures throughout South Asia due to the increase in greenhouse gas concentrations. This projected increase is of the order of 2°C to 4°C in the mid-21st century under the IPCC Scenario I992a in both minimum and maximum temperatures. Results from a more recent RCM, providing regional impacts for climate studies

(PRECIS) indicate that the night temperatures increase faster than the day temperatures, with the implication that cold extremes are very likely to be less severe in the future.

Precipitation and associated circulation systems

Most of the MMD-A_1B models project a decrease in precipitation in DJF (the dry season), and an increase during the rest of the year. The median change is 11% by the end of the 21st century, and seasonally is –5% in DJF and 11% in JJA, with a large inter-model spread. The probabilistic method of Tebaldi et al. (2004a) similarly shows a large spread, although only 3 of the 21 models project a decrease in annual precipitation. This qualitative agreement on increasing precipitation for most of the year is also supported by earlier AOGCM simulations.

In a study with four GCMs, Douville et al. (2000) found a significant spread in the summer monsoon precipitation anomalies despite a general weakening of the monsoon circulation. They concluded that the changes in atmospheric water content, precipitation and land surface hydrology under greenhouse forcing could be more important than the increase in the land-sea thermal gradient for the future evolution of monsoon precipitation. Stephenson et al. (2001) proposed that the consequences of climate change could manifest in different ways in the physical and dynamical components of monsoon circulation. Douville et al. (2000) also argue that the weakening of the *El Nino* southern oscillation (ENSO)-monsoon correlation could be explained by a possible increase in precipitable water as a result of global warming, rather than by an increased land-sea thermal gradient. However, model diagnostics using European centre hamburg model (ECHAM4) to investigate this aspect indicated that both the above mechanisms can play a role in monsoon changes in a greenhouse gas warming scenario. Ashrit et al. (2001) showed that the monsoon deficiency due to *El Niño* might not be as severe, while the favourable impact of *La Niña* seems to remain unchanged. In a later study using the Centre national de recherches météorologiques (CNRM) GCM, Ashrit et al. (2003) found that the simulated ENSO monsoon teleconnection shows a strong modulation on multi-decadal time scales, but no systematic change with increasing amounts of greenhouse gases.

Time-slice experiments with ECHAM4 indicated a general increase in the intensity of heavy rainfall events in the future, with large increases over the Arabian Sea and the tropical Indian Ocean, in northern Pakistan and northwest India, as well as in northeast India, Bangladesh and Myanmar (May, 2004). The HadRM2 RCM shows an overall decrease by up to 15 days in the annual number of rainy days over a large part of South Asia, under the IS92a scenario in the 2050s, but with an increase in the precipitation intensity as well as extreme precipitation (Krishna Kumar et al., 2003). Simulations with the PRECIS RCM also projected substantial increases in extreme precipitation over a large area, particularly over the west coast of India and west central India (Rupa Kumar et al., 2006). Dairaku & Emori (2006) show from a high-resolution AGCM simulation (about 1.5 degrees) that the increased extreme precipitation over land in South Asia would arise mainly from dynamic effects, that is, enhanced upward motion due to the northward shift of monsoon circulation. Based on regional HadRM2 simulations, Unnikrishnan et al. (2006) reported increases in the frequency as well as intensities of tropical cyclones in the 2050s under the IS92a scenario in the Bay of Bengal, which will cause more heavy precipitation in the surrounding coastal regions of South Asia, during both South-west and North-east monsoon seasons.

Agro-climatic analysis at micro level

Climate and weather are the important integrated factors determining the status of agriculture. The influence of weather on crop performance is operative even before the crop seed is sown. The physical, chemical and biological compositions of soils are greatly affected by weather. Weather also indirectly influences the outbreak of pest and diseases by interfering with agricultural operations. The yield potential of a crop is mainly depends on weather even though climate decide the choice of the crop. It regulates the living condition of plants and animals, their growth and multiplication. More than 50% of variation in yield of a crop is due to weather. Different set of analysis are used for analyzing the weather variables for different purpose (Table 1).

TABLE 1. *Types of analyses used in analyzing weather variables*

S. No.	Name of the analysis	Purpose
1	Co-efficient of variation for rainfall	Variability of rainfall
2	Initial probability for rainfall	Dependability of rainfall
3	Conditional probability for rainfall	Predicting rainfall
4	Onset & with drawl of monsoon	Agricultural planning
5	Length of growing period	Selection of crops and designing of suitable cropping pattern
6	Return period	Identifying the frequency of quantum of RF occurrence
7	Markov-chain analysis	Probability of wet and dry spell weeks
8	Trend analysis of climatic parameters	Statistical testing for trend, change and ran domness in rainfall and other time series data
9	Extreme event analysis	To find out weather phenomena that are at the extremes of the historical distribution

Co-efficient of variation for rainfall

Indian agriculture continues to face rainfall variability. The main features of rainfall variability are its quantity and distribution during the cropping period. Co-efficient of variation (CV) is used to understand such behavior.

Assessing the rainfall variability in terms of time and space enables for planning agricultural operations on a sustainable basis. There are several methods of variability analysis available and out of which estimation of co-efficient of variation is quite simple and more suited for agricultural purposes. This is because, there exists a strong relationship between CV and rainfall dependability. The greater the CV, the lesser is the dependability. Similarly, lower the rainfall, the greater the CV.

The formula used in this method is

$$CV = (\text{Standard Deviation}/\text{Mean}) \times 100$$

For doing such analysis, rainfall data from long term records are required at least for a block of 30 years as per the World Meteorological Organization (WMO) standard. The blocking of 30 years must be in such a way that starting year should be the beginning of a decade and terminal year should be the end of the decade. eg. 1961-90, 1971-2000. By experience, the following are the threshold levels of CV for any interpretation (Veeraputhiran et al., 2003).

Particulars	*Threshold level of CV*
Yearly RF	< 25%
Seasonal RF	< 50%
Monthly RF	< 100%
Weekly RF	< 150%
Daily RF	< 250%

Initial and conditional probabilities

The concept of estimation of probabilities with respect to given amount of rainfall is extremely useful for planning agricultural operations. Two types of probabilities i.e., initial and conditional probabilities are commonly used for analyzing the rainfall in respect of planning agricultural operations. This is very important because all the agricultural operations especially under dry land condition in a given area is dictated by rainfall events.

Initial probability

Initial probability (IP) indicates the minimum quantity of rainfall to be expected for a particular time series data. For computing the initial probability, the concerned time series rainfall data are arranged in descending order. The simple method used for computing initial probability is:

Initial probability = (Sample size (n) x Probability required in percentage (p))/100

For example if 30 years rainfall data were taken for analyzing 50 per cent rainfall probability means, IP = (30 x 50)/100 = 15

After arranging 30 years rainfall data of particular time series in descending order, identify the 15th number from the top and this would be 50 per cent probable rainfall amount.

Conditional probability

Chance of occurrence of particular quantity of rainfall for agricultural operations like sowing, weeding, etc.

Conditional probability (Cp) = $((\bar{x} - x)/ s)$

where,

$\bar{x}$ = mean weekly rainfall
x = rainfall required
σ = standard deviation

Since the resultant value does not fall under normal distribution it has to be referred to 'Z' table and multiplied by 100 to find out the actual probability in percentage. If the percentage is >60, it can be accounted for planning.

Length of growing period

Length of growing period (LGP) is defined as the period in which the soil is able to provide the moisture requirement of the crops to meet its evapotranspiration. This means that if a plant is grown in an identified LGP, the probability of getting soil moisture stress is negligible. In other words, it is a potential period for reaping potential productivity under selected agro techniques. Many methods *viz.,* Moisture adequacy index, Starting and termination rain method , Rainfall stability period method, Hargreeves Moisture availability index method, FAO model and Jeevananda Reddy method have been employed to identify LGP of a particular region (Raja et al., 2011).

In respect of starting and termination rain method, the date of onset and the date of withdrawal of seasonal rainfall are taken into account and the length of period between onset and termination will be taken as LGP. The main feature of Indian rainfall is spatial and temporal variability and as a result, intra-seasonal variability is of a great importance. Hence in this method, the length of dry and wet spells within the growing period could not be brought out which again is a major limitation for agricultural planning.

Using of probability of weekly rainfall for computing Moisture availability index (MAI) under Hargreeves method is varying between different rainfall situations (high rainfall areas, assured rainfall areas and scanty rainfall areas). Hence assessing the right probability for weekly rainfall would be an additional exercise for this method.

The FAO model was used by National Bureau of Soil Survey and Land Use Planning, Nagpur to compute LGP for classifying the Indian areas into different Agro Ecological Regions and Agro Ecological Zones. In this method, if the consecutive monthly rainfall is more than 50% of potential evapotranspiration (PET) of that month, then this sequence is taken as LGP. In addition, the stored soil moisture at the end of the season is accounted in computing LGP. The limitation of this method is handling of macro level data on monthly basis. For proper agricultural planning, any method that uses weekly data would be more relevant.

The better available method would be Jeevananda Reddy method, which encompasses weekly rainfall and weekly PET. This method uses two approaches one for computing simple R/PE ratio; the other one is the computation of 14 weeks moving average. The quantity 14 weeks indicates 98 days, which is a safety period for a dry land crop to complete its life cycle from seeding to harvest.

Markov-chain analysis

Agricultural operations are determined by the certain amount of rainfall received in a period. There are specific amounts of rainfall required for the activities like land preparation, sowing and for various agricultural activities. Hence, estimation of probabilities with respect to a given amount of rainfall is useful for rainfed agricultural planning especially in semiarid region. Initial probability rainfall analysis will give percentage probability to get certain amount of rainfall in a given week. Probability of wet week is denoted as P(W) and dry week as P(D). Conditional probability rainfall analysis will give the percentage probability for wet week followed by wet week [P(W/W)], wet week followed by dry week [P(W/D)], dry week followed by dry week [P(D/D)] and dry week followed by wet week [P(D/W)]. It is also important to find out percentage probability of consecutive wet weeks (2W, 3W, 4W) and consecutive dry weeks (2D, 3D, 4D). Several techniques are in use to work out wet and dry spells .The initial and conditional probabilities as per the first order Markov chain model is widely used world over to understand the crop growing seasons based on dry and wet spells.

Trend analysis of climatic parameters

Intergovernmental panel on climate change (IPCC) reported that the impact of climate change is severe in lower latitudes, especially in seasonally dry and tropical regions, where crop productivity is projected to decrease for even small local temperature increases (1 to 2°C), which would increase the risk of hunger (medium confidence). Decreases in precipitation are predicted by more than 90% of climate model simulations by the end of the 21st century for the northern and southern sub-tropics. However, agricultural productivity can also be increased, costs reduced and impending crop shortfalls mitigated or avoided through the judicious use of information and knowledge about climate and weather, including early warning and agro-meteorological advisories. Time series analysis of rainfall and other meteorological parameters helps in understanding the behavior of a particular weather parameter over time in that region.

TREND is software designed to facilitate statistical testing for trend, change and randomness in hydrological and other time series data. TREND has 12 statistical tests, based on the WMO/UNESCO Expert Workshop on trend/ change detection. The TREND software program can be downloaded from the TREND homepage www.toolkit.net.au/trend. TREND requires a continuous time series as input data in comma separated value file (.csv file). TREND displays as an output the value of the test statistic, the critical values of the test statistic at 0.01 (90 % significant level), 0.05 (95 % significant level) and 0.1 (90 % significant level), and a statement of the test result, for all the statistical tests selected by the user.

Extreme event analysis

The weather outlook is of great help to agriculture operations. Certain rainfall amount and temperature thresholds have a great influence on crop production. Advises are given to the agricultural community about extreme events like heavy rainfall, prolong dry spell, and high and low temperature event would help to reduce losses to agriculture.

Goswami et al. (2006) using a daily rainfall data set found (i) significant rising trends in the frequency and the magnitude of extreme rain events and (ii) a significant decreasing trend in the frequency of moderate events over central India during the monsoon seasons from 1951 to 2000 and predicted a substantial increase in hazards related to heavy rain over central India in the future.

The frequency of droughts has varied over the decades in India. From 1899 to 1920, there were seven drought years. The incidence of drought came down between 1941 and 1965 when the country witnessed just three drought years. Again, during 1965-87, of the 21 years, 10 were drought years and the increased frequency was attributed to the ENSO. Among the drought years, the 1987 drought was one of the worst droughts of 20th Century, with an overall rainfall deficiency of 19%. It affected 59-60% of the crop area and a population of 285 million. In 2002 too, the overall rainfall deficiency for the country as a whole was 19%. Over 300 million people spread over 18 states were affected by the drought in varying degrees. Food grains production registered the steepest fall of 29 million tonnes (Samra, 2004). The frequency of occurrence of drought in different meteorological sub-divisions of India is given in Table 2.

TABLE 2. *Probability of occurrence of drought in different meteorological sub-divisions of India*

Meteorological sub-division	Frequency of deficient rainfall (75% of normal or less)
Assam	Very rare (Once in 15 years)
West Bengal, Madhya Pradesh, Konkan, Bihar and Odisha	Once in 5 years
South interior, Karnataka, Eastern Uttar Pradesh & Vidarbha	Once in 4 years
Gujarat, East Rajasthan, Western Uttar Pradesh	Once in 3 years
Tamil Nadu, Jammu & Kashmir and Telengana	Once in 2.5 years
West Rajasthan	Once in 2 years

Impact of climate variablity/ change on rice

The increase in temperature especially that of mean minimum night time temperature has adverse effect on rice productivity in terms of increased night respiration. Farmers have to adopt with the growing challenge of the increase in extreme climatic events associated with climate change, such as increasing severity and frequency of floods and drought, and their effect on crops, in particular rice, which is a major staple crop in India.

In predominantly rainfed eastern India, as a result of climate variability/change, there is change in monsoon pattern from the normal, which adds stress to the prediction of monsoon rain. The two components of seasonal monsoon rainfall which most influence the success of a given growing season are its total amount and its distribution. Though in nearly every year, sufficient total precipitation is received during the growing season the extreme distribution in limited rainy days leads to floods, and drought.

The impact of projected global warming on crop yields has been evaluated by indirect methods using simulation models. However, direct studies on the effects of observed climate change on crop growth and yield could provide more accurate information for assessing the impact of climate change on crop production. Peng et al. (2004) analyzed weather data at the International Rice Research Institute Farm from 1979 to 2003 to examine temperature trends and the relationship between rice yield and temperature by using data from irrigated field experiments conducted at the International Rice Research Institute Farm from 1992 to 2003. It was found that annual mean maximum and minimum temperatures have increased by 0.35°C and 1.13°C, respectively, for the period 1979–2003 and a close linkage between rice grain yield and mean minimum temperature during the dry cropping season (January to April). Grain yield declined by 10% for each 1°C increase in growing-season minimum temperature in the dry season, whereas the effect of maximum temperature on crop yield was insignificant. This finding provides a direct evidence of decreased rice yields from increased night time temperature associated with global warming.

References

Ashrit, R.G., Douville, H., & Rupa Kumar, K. (2003). Response of the Indian monsoon and ENSO-monsoon teleconnection to enhanced greenhouse effect in the CNRM coupled model. *Journal of the Meteorological Society of Japan*, 81, 779-803.

Ashrit, R.G., Rupa Kumar, K., & Krishna Kumar, K. (2001). ENSO monsoon relationships in a greenhouse warming scenario. *Geophysical Research Letters,* 29, 1727-1730.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X., Held, I., Jones, R., Kolli, R.K., Kwon, W.T., Laprise, R., Magaña Rueda, V., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., & Whetton, P. (2007). Regional climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge and New York: Cambridge University Press.

Dairaku, K., & Emori, S. (2006). Dynamic and thermodynamic influences on intensified daily rainfall during the Asian summer monsoon under doubled atmospheric CO_2 conditions. *Geophysical Research Letters,* 33, L01704, 5.

Douville, H., et al. (2000). Impact of CO_2 doubling on the Asian summer monsoon: Robust versus model dependent responses. *Journal of the Meteorological Society of Japan*, 78, 1-19.

Fox-Rabinovitz, M., Cote, J., Dugas, B., D´equ´e, M., McGregor, J.L., et al. (2008). Stretched-grid Model Intercomparison Project: Decadal regional climate simulations with enhanced variable and uniform-resolution GCMs. *Meteorology and Atmospheric Physics,* 100, 159-178.

Goswami, B.N., Venugopal, V., Sengupta, D., Madhusoodanan, M.S., & Xavier, P.K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science,* 314, 1442-1445.

Grotch, S.L., & MacCracken, M.C. (1991). The use of general circulation models to predict regional climatic change. *Journal of Climate,* 4, 286-303.

Hein, L., Metzger, M.J., & Leemans, R. (2009). The local impacts of climate change in the Ferlo, Western Sahel. *Climatic Change,* 93, 465-483.

Krishna Kumar, K., et al. (2003). Future scenarios of extreme rainfall and temperature over India. In *Proceedings of the Workshop on Scenarios and future emissions*, Indian Institute of Management (IIM), Ahmedabad, July 22, 2003. (pp. 56-68). New Delhi: NATCOM Project Management Cell, Ministry of Environment and Forests, Government of India.

Lal, M., McGregor, J.L., & Nguyen, K.C. (2008). Very high resolution climate simulation over Fiji using a global variable-resolution model. *Climate Dynamics,* 30, 203-305.

May, W. (2004). Simulation of the variability and extremes of daily rainfall during the Indian summer monsoon for present and future times in a global time-slice experiment. *Climate Dynamics,* 22, 183-204.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., et al. (2007). Global climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, et al. (Eds.), *Climate change 2007: The physical science basis.* Cambridge and New York: Cambridge University Press.

Mizuta, R., Oouchi, K., Yoshimura, H., Noda, A., Katayama, K., et al. (2006). 20-km-mesh global climate simulations using JMA-GSM model—mean climate states. *Journal of the Meteorological Society of Japan*, 84, 165-185.

Olson, J.M., Alagarswamy, G., Andresen, J.A., Campbell, D.J., Davis, A.Y., Ge, J., Huebner, M., Lofgren, B.M., Lusch, D.P., & Moore, N.J. (2008). Integrating diverse methods to understand climate-land interactions in East Africa. *Geoforum,* 39, 898-911.

Peng, Shaobing, Jianliang Huang, John E. Sheehy, Rebecca C. Laza, Romeo M. Visperas, Xuhua Zhong, Grace S. Centeno, Gurdev S. Khush and Kenneth G. Cassman. (2004). Rice yields decline with higher night temperature from global warming. *PNAS*, 101(27), 9971 -9975.

Raja, R., Solaimalai, A., Subbulakshmi, S., Jawahar, D., & Rao, V.U.M. (2011). Length of growing period for Tamil Nadu. (pp. 275). Tamil Nadu: Agricultural Research Station, Kovilpatti.

Randall, D.A., Wood, R.A., Bony, S., Colman, R., Fichefet, T., Fyfe, J., Kattsov, V., Pitman, A., Shukla, J., Srinivasan, J., Stouffer, R.J., Sumi, A., & Taylor, K.E. (2007). Climate models and their evaluation. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, et al. (Eds.), *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge and New York: Cambridge University Press.

Rummukainen, M. (2010). State-of-the-art with regional climate models. *WIREs Climate Change,* 1, 82-96.

Rupa Kumar, K., Sahai, A.K., Krishna Kumar, K., Patwardhan, S.K., Mishra, P.K., Revadekar, J.V., Kamala, K., & Pantet, G.B. (2006). High-resolution climate change scenarios for India for the 21st century. *Current Science*, 90(3), 334-345.

Samra, J.S. (2004). *Review and analysis of drought monitoring, declaration and management in India*. Working paper 84. Drought series paper 2. Colombo: International water management Institute.

Stephenson, D.B., Douville, H., & Rupa Kumar, K. (2001). Searching for a fingerprint of global warming in the Asian summer monsoon. *Mausam*, 52, 213-220.

Tebaldi, C., Mearns, L.O., Nychka, D., & Smith, R. (2004). Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations. *Geophysical Research Letters,* 31, L24213.

Thornton, P.K., Jones, P.G., Alagarswamy, G., Andresen, J., & Herrero, M. (2010). Adapting to climate change: Agricultural system and household impacts in East Africa. *Agricultural Systems,* 103, 73-82.

Unnikrishnan, A.S., Kumar, K.R., Fernandes, S.E., Michael, G.S., & Patwardhan, S.K. (2006). Sea level changes along the Indian coast: Observations and projections. *Current Science,* 90(3), 362-368.

Veeraputhiran, R., Karthikeyan, R., Geethalakshmi, V., Selvaraju, R., Sundarsingh, S.D., & Balasubramanian, T.N. (2003). Crop planning – Climate atlas (1st ed.). (pp. 157). Coimbatore, Tamil Nadu: A.E. Publications.

*****

Chapter 10

Cropping system approach to cope with climate change

K. Srinivasa Rao
Central Rice Research Institute, Cuttack, Odisha, India
e-mail: ksrao_52@hotmail.com

The continuing population pressure in the country will demand substantial increase in food, feed, fodder, fiber and fuel production over the next few decades to be able to maintain self sufficiency and also meet export requirement. Our population has already crossed one billion mark and is estimated to stabilize around 1.5 billion by the year 2030. The demand for food grains is estimated at 240 m t by the end of XI plan period. Keeping this in view, the government of India launched the National Food Security Mission to achieve the production of additional 10, 8 and 2 m t of rice, wheat and pulses, respectively. The task is quite challenging and the options available are very limited in view of plateauing trend of yield in high productive areas, decreasing and degrading land, water, labour and other inputs. Among the various possible approaches to achieve this target is to increase the productivity per unit time and area *i.e.,* by raising two or more crops per year through multiple, relay and intercropping both in irrigated and rainfed areas; and by utilizing the available resources more efficiently. With the availability of shorter duration varieties of different crops the scope for growing two or more crops in a year is continuously increasing. Hence, emphasis needs to be laid on identification of suitable cropping systems with higher and stable yields and/ or profit in different agro-ecological regions. Further, in response to commercialization of agriculture also, it is important to shift from routine food grain production system to newer crops/cropping systems depending upon the climatic conditions as well as agro-ecosystems under different rice-based production system in order to make agriculture an attractive, profitable and sustainable business.

The change in climate has been attributed to global warming and has many facets, including changes in long term trend in temperature and rainfall regimes as well as increasing year-to-year variability and a greater prevalence of extreme events. Agricultural systems will be affected by both short and long term changes in climate, and will have serious implications on rural livelihoods, particularly of the poor being the most vulnerable. The impact of climate change poses serious threats to productivity and sustainability of various rice-based cropping systems including rice-wheat cropping system, the backbone of food security of India. Despite some projected increase in photosynthesis caused by increased concentrations of carbon dioxide, increased temperature will have a far greater detrimental effect, resulting reduced crop productivity. Conservation agriculture involving continuous minimum mechanical soil disturbance, permanent organic soil cover and diversified crop rotations provides opportunities for mitigating greenhouse gas emission and climate change adaptation.

Rice and rice-based cropping systems

Rice (*Oryza sativa* L.) is the most important staple food crop in India that holds key to food security. Rice-based production systems provide livelihood for more than 50 million households. In India, rice is grown on more than 44 m ha under three major ecosystems: rainfed uplands (16%

area), irrigated medium lands (45%) and rainfed lowlands (39%), with a productivity of 0.87, 2.24 and 1.55 t ha^{-1}, respectively. The crop in *rabi*/summer is grown on nearly 3 m ha mostly with irrigation in the eastern and southern states, but the *kharif* crop is grown under a wide range of soil and climatic conditions throughout the country. Rice cultivation in eastern India is characterized by predominantly rainfed culture (70%), mono-cropping, low fertilizer use and traditional varieties. On the other hand under irrigated conditions, input intensive rice-based cropping systems involving cereals, pulses, oilseeds, tuber and fiber crops are practiced.

With the introduction of high yielding photo and thermo insensitive rice varieties of relatively shorter duration, there was remarkable changes in the cropping system concept (Sharma et al., 2004). A large number of crops are now being grown after rice under different ecologies based on soil and prevailing agro-climatic conditions in major rice growing states of the country. Out of the major cropping systems identified by the Project Directorate for Farming Systems Research, rice-based system occupies the largest area of about 28 m ha in India. Among the rice-based cropping systems, the major ones are rice-wheat (9.8 m ha), rice-rice (5.9 m ha), rice-fallow (4.4 m ha), rice-pulses (4.4 m ha), rice-vegetables (1.2 m ha), rice-groundnut (1.0 m ha), rice-mustard (0.5 m ha), rice-potato (0.5 m ha) and rice-sugarcane (0.4 m ha) (Yadav & Subba Rao, 2001). Preference of rice-based cropping systems in different parts is based on location advantages that include ecology, land topography, soil type, and availability of water and marketing facilities. For example, rice-wheat and rice-rice systems are practiced in irrigated ecology whereas rice-lathyrus, rice-gram or rice-blackgram/ greengram, etc. are practiced in rainfed uplands and lowlands.

Rainfed uplands

In India, 85% of the upland rice area is located in the states of Assam, Bihar, West Bengal, Odisha and eastern parts of Madhya Pradesh and Uttar Pradesh. The rainfall in this zone is in the range of 1000 to 2000 mm or more and temperature ranges from 25 to 41°C in July and from 6 to 25°C in January. Red laterite and lateritic soil such as mixed red and yellow, red sandy, red loam, lateritic and mixed red and brown hill soils account for about 55% of the total rice area in the east zone. Next in the order of occurrence is alluvial soil, which occupies about 27% of the total rice area. Rice is grown under rainfed condition in these uplands in monsoon season.

In rainfed uplands, shorter duration (90-105 days) rice varieties like Vandana, Kalinga III, Anjali, NDR 97, Annada are to be grown by sowing during the onset of monsoon, so that the field should be vacated early for the second crop (Saha et al., 2003). Crops like mustard, castor, linseed, safflower, blackgram, lentil, horsegram can be grown by taking advantage of residual soil moisture and late monsoon rains. The second crop should be sown as early as possible (within a week) after harvest of rice to get the advantage of residual soil moisture. Mulching by using rice straw also helps to conserve the soil moisture under such situations. In bunded uplands, where there is still possibility for giving at least one or two irrigation through harvested rain water, crops like sunflower, gram, tomato, etc. can be successfully grown after harvest of wet season rice. The short duration improved varieties of the above crops can give a good return under such situations. Intercropping of rice with short duration pulses like greengram, blackgram, pigeonpea or oilseeds like groundnut also shows a good prospect for improving productivity and farmers' income. Intercropping of upland rice with pigeon pea (4: 1 row ratio) recorded higher rice equivalent yield and net return over sole crop under Institute Village Linkage Programme in Cuttack district of Odisha (Anonymous, 2005). Rice-based inter cropping with pigeon pea, blackgram and groundnut recorded much higher (3.3-3.9 kg per ha-mm) rainwater use efficiency.

Irrigated medium lands

Under irrigated condition majority of rice is grown in wet season (June to October) but around 4 m ha is under dry season (November to May). The important cropping systems followed under irrigated medium land situations are rice-rice, rice-wheat, rice-winter maize, rice-groundnut, rice-sunflower, rice-potato, rice-mustard, rice-gram, rice-winter vegetables, etc. with 200% cropping intensity. There is still scope to introduce a third crop of short duration pulses like cowpea, greengram, blackgram or oilseed crops like sesame in areas where irrigation facilities are available to provide 1-2 life saving irrigation to the third crop. In West Bengal, rice-potato-sesame, rice-wheat-greengram, rice-wheat-jute are found to be remunerative. Rice-potato-sesame, rice-maize-cowpea, rice-sunflower-greengram, rice-groundnut-sesame are found to be promising in Odisha.

In Assam, Regional rainfed lowland rice research station, Gerua (a Research Station of CRRI, Cuttack) has standardized production technology for year round rice growing (rice-rice-rice cropping sequence with 300% cropping intensity) to meet household food security and year round employment generation for small and marginal farmers with land holding less than 1 ha. In Punjab, the cropping system with 300% intensity such as rice-potato-sunflower, rice-potato-winter maize and rice-toria-sunflower have been found to be more productive than conventional systems of 200% cropping intensity with rice-wheat or rice-winter maize. Early medium to medium duration (120-135 days) rice varieties like Naveen, Ratna, IR 36, Padmini, Khitish, Shatabdi, Tapaswini provides good scope to advance the sowing time of the second crop by late October to early November so that the third crop (70-90 days) can be accommodated during February-April.

Rainfed lowlands

Rainfed lowland rice is grown in around 13 m ha, mostly in eastern India, where soil moisture is available for longer period, rice varieties of 140 days duration, mostly photosensitive types are grown and harvested from mid November to mid December. The water depth varies in rainfed lowlands and it can be shallow up to 25 cm, and medium-deep waterlogged up to 50 cm. Deep-water rice is grown in areas where water depth is more than 50 cm up to 2 m, and around 4 m ha area is under cultivation in eastern India with an average productivity of 0.8 t ha^{-1}. Most of the deep water rice area in West Bengal, Assam, North-east Bihar, and coastal Odisha is now being under *boro* and dry season rice due to low productivity of deep water rice.

Farmers traditionally grow tall *indica* types, which are prone to lodging and are of low productivity. The varieties grown in these land situations are generally medium to long (130-180 days) duration depending upon the water depths in the fields where they are grown and should have tolerance to drought initially and to submergence at later stage; photosensitivity; moderate to high tillering abilities; tolerance to pests and diseases and elongation ability in semi-deep and deep situations. The ideal plant height for shallow lowlands is 110-130 cm, 130-150 cm for medium deep situations and > 150 cm for deep water areas.

Medium to long duration (140-155 days) rice varieties like Swarna, Vijeta, Surendra, Moti, Pooja, Pankaj, etc. are usually grown in rainfed shallow lowlands of eastern India. Short duration pulses like greengram, blackgram, etc. can be grown after rice harvest with residual soil moisture. There is a little scope to take a second crop in areas where soil moisture recedes fast during November onwards. Under such situation, crops like lathyrus, field pea, linseed, lentil, blackgram can be raised as relay/paira crop by sowing the second crop in the standing crop of rice 10-15 days before harvesting (Saha & Moharana, 2005). In certain areas of eastern India, crops like sunflower, groundnut, watermelon, okra, sweet potato can be raised with limited irrigations (2-3) by utilizing the harvested rainwater stored in small farm ponds.

Long duration (155-180 days) photosensitive rice varieties like Varshadhan, Gayatri, Savitri, Sarala, Panidhan, Durga, Tulsi, Kalashree, Sabita and Nalini are grown predominantly in intermediate deep and deep water rice ecology of east coast and lower Gangetic Plains of India. These areas are having potential to harvest rainwater during monsoon period (June-September) that can help to grow several winter vegetables like pumpkin, bitter gourd, okra, chilli, along with other crops like blackgram, greengram, sunflower, groundnut, watermelon, sesame, etc. during the dry season (January–early April). The salt affected coastal areas are generally rainfed and mono-cropped with rice. Land mostly remains fallow during the dry season due to soil salinity and unavailability of fresh water. However, rice and certain salt tolerant crops like sunflower, chilli, watermelon, sugar beet, cotton, etc. are grown in pockets depending on the availability of harvested rainwater, soil and climatic conditions (Singh et al., 2006). Pulses like blackgram, greengram, cowpea, etc. and groundnut is also grown in some areas having mild salinity.

Major sustainability issues in cropping systems

- ☐ In semi-arid ecosystem intensive water use in rice-wheat cropping system led to increased salinization in many areas. There are indications of yield declines where balanced nutrient application has not been made. Deficiency of micronutrients has been observed.
- ☐ The problem of depletion of underground water in semi-arid areas of Punjab and Haryana needs to be addressed through development of alternate cropping system under limited water supply.
- ☐ To reduce the use of purchased inputs by small farmers, green manure should be introduced in the rice-wheat, rice-rice system. Fifty percent of nitrogen requirement of rice could be substituted by growing *Sesbania* before transplanting rice.
- ☐ In the sub-humid ecosystem, reduction in wheat yield following rice is due to delayed wheat planting, low plant stand and poor nutrient management. Delayed wheat planting is associated with excess soil moisture at the time of rice harvest. Higher seed rate and nutrient can compensate wheat yield losses to some extent.

Management of rice-based cropping systems

The rice-based cropping systems will continue to be important cropping systems in India in the years to come. Therefore, there is a strong need to monitor these systems in terms of nutrient dynamics and to develop efficient integrated nutrient supply and management system in different regions using locally available resources like compost, farm yard manure, farm wastes, crop residues and green manures. There is also a need to monitor insect, disease and weed problems, water table and water harvesting techniques. Crop establishment of succeeding crops after rice and dry seeding methods of rice need greater attention. There is a need for the choice of genotypes and introduction of short duration, photoperiod insensitive varieties, the possibilities for crop intensification/diversification have to be studied. Thus, ample scope exists for improving the total land productivity through generation of appropriate production technologies for diverse agro-climatic situations.

Conservation agriculture

Conservation agriculture is characterized by three principles which are linked to each other, namely continuous minimum mechanical soil disturbance, permanent organic soil cover and diversified crop rotations in the case of annual crops or plant associations in case of perennial crops which provides opportunities for mitigating greenhouse gases (GHGs) emission and climate change adaptation. Recent research efforts have attempted to develop resource conserving technologies (RCTs), which are more resource efficient, use less inputs, improve production and income, and reduce GHGs emission compared to the conventional practices. Some of these technologies are being adopted by the farmers on large scale, which would help farmers in combating climate change to a considerable extent. Specific impacts of various RCTs on GHGs mitigation are briefly discussed below:

Zero tillage

Conventional land preparation practices for wheat after rice involves as many as 10-12 tractor passes. Changing to a zero-till system on 1 ha of land would save 98 liters of diesel and approximately 1 million liters of irrigation water besides reducing about a quarter tonne less emission of carbon dioxide (CO_2), the principal contributor to global warming. However, impact of zero tillage on methane (CH_4) and nitrous oxide (N_2O) emissions have showed contrasting results with lower, equal and higher compared to the conventional systems depending upon the soil type and water management. Zero tillage also allows rice-wheat farmers to sow wheat sooner after rice harvest, so the crop heads and fill the grain before the onset of pre-monsoon hot weather.

Laser aided land leveling

Laser leveling of uneven field reduces water use allowing crop to grow in water limited condition. It also reduces fuel consumption because of efficient use of tractor and reduces GHGs emission, particularly CO_2. Several other benefits such as operational efficiency, weed control efficiency, water use efficiency, nutrient use efficiency, crop productivity and economic returns and environmental benefits have also been reported due to laser aided land leveling compared to conventional practice of land leveling.

Direct drill seeding of rice

Direct drill seeding of rice (DSR) could be a potential option for reducing CH_4 emission. Methane is emitted from soil when it is continuously submerged as in the case of conventional puddle transplanted rice. The DSR crop does not require continuous soil submergence, thereby either reducing or totally eliminating CH_4 emission when it is grown as an aerobic crop. Moreover, deeper root growth of DSR crop provides better tolerance to water and heat stress. Besides the unpuddled soil in DSR does not crack with moisture stress unlike puddle soil which helps to increase yield significantly.

Crop diversification

Diversification is growing a range of crops suited to different sowing and harvesting times, assists in achieving sustainable productivity by allowing farmers to employ biological cycles to minimize inputs, maximize yields, conserve the resource base, reduce risk due to both environmental and economic factors. The RCTs such as bed planting and zero tillage expand the windows of crop diversification. The farmers of rice-wheat belt have taken the initiative to diversify their agriculture by including short duration crops such as potato, soybean, blackgram, greengram, cowpea, pea, mustard, and maize into different combinations. Such diversification would not only improve income, employment and soil health but also reduce water use and GHGs emission and more adaptability to heat and water stress.

Raised bed planting

In raised bed planting a part of soil surface always remains unsubmerged. Thus it not only reduces water use and improves drainage but also reduces methane emission. Crops on beds with residue retained on surface is less prone to lodging and more tolerant to water stress, thereby making it more adaptable to unfavourable climate.

Leaf colour chart

The most efficient management practice to minimize plant N uptake and minimize N loss is to synchronize supply with plant demand. The use of leaf colour chart (LCC) promotes a need-based N application to rice crop that saves N and increases N use efficiency. As a result there will be less accumulation of mineral forms of N (NH_4 and NO_3) within the crop root zone and hence less losses of N and N_2O emission. Besides, because of healthier plant growth due to timely application of N fertilizer, damages caused by insects were reported to have been reduced.

Integrated nutrient management

Food security and soil health are two important concerns in Indian agriculture. Integrated nutrient management (INM) in crop production, particularly in rice-based cropping systems, plays a crucial role in the pursuit of these two set missions. Integrated nutrient management is achieved through combined use of different sources of plant nutrients such as chemical fertilizers, organic manures, green manures, crop residues, bio-fertilizers, industrial wastes and soil conditioners depending upon their availability and suitability in a specific agro-ecological situation (Hegde & Dwivedi, 1992; Panda & Singh, 1998). It also includes scientific management of these sources of nutrients for securing optimum crop yield and soil fertility improvement. According to Roy & Ange (1991), the basic concept underlying integrated plant nutrient supply and management system (IPNS) is the maintenance or adjustment of soil fertility and of plant nutrient supply to an optimum level for sustaining the desired crop productivity through optimization of the benefits from all possible sources of plant nutrients in an integrated manner. Economic viability and ecological sustainability are also major considerations in INM. In a holistic approach, the INM practices are designed and adopted to increase the quantity and quality of crop produce, decrease nutrient losses, increase the efficiency of applied and native nutrients, improve soil health, economize on fertilizer use, protect the environment and minimize the energy consumption in agriculture.

Takkar et al. (1998) considered a conceptual framework of IPNS which includes four distinct integral components *viz.,* (i) on-site nutrient resource generation, (ii) mobilization of off-site nutrient resources, (iii) resource integration and (iv) resource management. On-site nutrient resource generation is mostly achieved through green manuring and recycling of crop residues. Mobilization of off-site nutrient resources includes three categories of sources of nutrients *viz*., bio-organic wastes (FYM and compost), bio-organisms (bio-fertilizers) and mineral resources (synthetic and mineral fertilizers). Resource integration, the guiding principle of INM not only supplements the fertilizer use but also provides the benefits of positive interaction for various nutrient sources in restoring soil fertility. It also ensures balanced crop nutrition and synergetic interaction in a cropping system for sustainable agriculture. The nutrient resource management improves the nutrient use efficiency by checking nutrient losses from soil, optimizing nutrient resource combination and monitoring plant nutrient flows. It also addresses the soil related problems limiting crop growth such as soil acidity, salinity, alkalinity, soil compaction, etc. Ultimately, it imparts resilience against the soil degrading processes and promotes quality of the environment.

Because of several reasons including those of soil health care and high crop yield, it is necessary to supplement/complement chemical fertilizer application with the other components of INM which are mostly organic in nature. Results of research on INM in irrigated rice revealed that at N level of 60 kg ha^{-1}, combined application of urea and *dhaincha* green manure/ *Azolla*/ FYM at 1:1 ratio on N level basis, produced comparable grain yield to that of urea alone. However, at N level of 90 kg ha^{-1}, INM practices involving *dhaincha* green manure or *Azolla* dual crop were superior to the chemical source of N (Panda et al., 1991)

Conclusions

The overwhelming importance of rice and rice-based cropping systems for the food security of India requires a thorough assessment of the rice resource base and the impact of rice cultivation on the environment. The decline in soil and water quality in rice-based systems is a major global issue. The situation is going to be worse in the event of possible global warming, which has negative impact on yield and soil fertility. Therefore, the systems should be constantly monitored in terms of their natural resource base. Suitable quantitative models that incorporate the relevant bio-physical and socioeconomic interactions to permit quantitative assessment of rice cultivation in relation to the environment and natural resources need to be developed. An environmental impact assessment should include a social impact assessment, strategic environmental assessment, and life cycle analysis of the implementation of rice technologies. Holistic and eco-regional strategies to manage, preserve and improve the nutrient resource base and soil qualities in rice-based cropping systems have to be strengthened.

Climate change poses serious threats to productivity and sustainability of various cropping systems. Recent efforts have attempted to develop and deliver resource conservation technologies involving no- or minimum tillage with direct seeding, and bed planting with residue mulch, innovations in residue management to avoid straw burning, and crop diversification as alternatives to the conventional management practices for improving productivity and sustainability of important rice-based cropping systems. The wide scale adoption of any improved cropping system by the farming community depends mostly on socio-economic factors such as labour availability, credit requirement, cost of inputs, processing, marketability and price of produce, risk involved and social acceptability of the new system. Thus before designing a particular cropping system, care should be given on its economic feasibility. Emphasis should also be given for developing suitable rice-based farming system model by incorporating animal components into the system to enhance the overall economy and standard of living of poor farm community.

References

Anonymous. (2005). National Agricultural Technology Project, Rainfed Agro Ecosystem, Technology assessment and refinement through Institute Village Linkage Programme. (pp.15-16). Hyderabad, India: Central Research Institute for Dryland Agriculture.

Hegde, D.M., & Dwivedi, B.S. (1992). Nutrient management in rice-wheat cropping system in India. *Fertilizer News,* 37, 27-41.

Panda, D., & Singh, D.P. (1998). In *Rainfed rice for sustainable food security*. (pp. 239-258). Cuttack: Central Rice Research Institute.

Panda, D., Samantaray, R.N., Mohanty, S.K., & Patnaik, S. (1991). Green manuring with *Sesbania aculeate*: Its role in nitrogen nutrition and yield of rice. In S.K. Dutta, C. Sloger (Eds.), *Biological nitrogen fixation associated with rice production.* (pp. 305-313). New Delhi: Oxford and IBH Pub. Co.

Roy, R.N., & Ange, A.L. (1991). Integrated plant nutrition systems (IPNS) and sustainable agriculture. In Proceedings of FAI Annual Seminar. pp SV/1-1-SV/1-12. New Delhi: Fertilizer Association of India.

Saha, S., & Moharana, M. (2005). *Utera* cultivation - A viable technology option for rainfed shallow lowland of coastal Orissa. *Indian Farming*, 56(3), 13-15 & 19.

Saha, S., Dani, R.C., & Beura, J. (2003). Integrated crop management for rainfed upland rice. *NATP Technical Bulletin No. 14.* Central Rice Research Institute.

Sharma, S.K., Subbaiah, S.V., Rao, K.S., & Gangwar, K.S. (2004). Rice-based cropping system for rainfed upland, rainfed lowland and irrigated areas of different states of India. In *Proceedings of national symposium on "Recent advances in rice-based farming systems"*. Central Rice Research Institute, Cuttack, pp. 36-57.

Singh, D.P., Mahata, K.R., Saha, S., & Ismail, A.M. (2006). Crop diversification options for rice-based cropping system for higher land and water productivity in coastal saline areas of eastern India. In *Abrtr. 2nd International Rice Congress on "Science, technology and trade for peace and prosperity"*. p 475. New Delhi: IARI.

Takkar, P.N., Kundu, S., & Biswas, A.K. (1998). In A. Swarup et al. (Eds.), *Long term soil fertility management through Integrated Plant Nutrient Supply*. (pp. 78-88). Bhopal, India: Indian Institute of Soil Science.

Yadav, R.L. & Subba Rao, A.V.M. (2001). *Atlas of cropping systems in India.* (pp. 96). Modipuram, Meerut, India: Project Directorate for Cropping Systems Research.

*****

Chapter 11

Resource conservation technologies in rice based cropping systems: A climate change mitigation option

Rahul Tripathi[1*], **Mohammad Shahid**[1], **A.K.Nayak**[1] **and S.S. Pal**[2]
[1]Central Rice Research Institute, Cuttack, Odisha, India
[2]Project Directorate of Farming System Research, Modipuram, Uttar Pradesh, India
*e-mail: rahulcrri@gmail.com

Rice based cropping systems accounts for more than half of the total acreage in South Asia, where rice is grown in sequence with rice or upland crops like wheat, maize or legumes. Rice based cropping systems occupy 13.5 m ha in the Indo-Gangetic Plains (IGP) of South Asia (Gupta & Seth, 2007) which provides food security and livelihoods for millions. The productivity and sustainability of the rice based systems are threatened because of (1) inefficient use of inputs such as fertilizer, water and labor; (2) increasing scarcity of resources, especially water and labor; (3) changing climate; (4) changes in land use (cropping practices and cropping systems) driven by a shortage of water and labor; (5) socio-economic changes (urbanization, labor migration, changing attitude of people to shun away from farm work); and (6) increasing farm pollution (Ladha et al., 2009). Countries with a large population like China and India face the challenge of maintaining and increasing high yield levels in a scenario of increasing climatic variability. Over the last few decades, the growth in agricultural production has come mainly from yield increase and to a lesser extent from area expansion. Now the agricultural land available per capita is expected to decline (FAO, 2002). Furthermore, in high intensity agricultural production areas, yield increase seems to have reached a ceiling despite higher input use. Crop yields even decline in some cases, for example in the grain producing areas of Punjab in India (Aulakh, 2005). Water is one of the most precious natural resources for agricultural production and agriculture accounts for 70 percent of water use (FAO, 2002). In the Indian state of Punjab, characterized by intensive irrigated agriculture, the groundwater table is falling at a rate of 0.7 m per year (Aulakh, 2005). Agriculture contributes to the problem by pumping excess water and by sealing and compacting the soils so that excess rain water can not infiltrate and recharge the aquifer; one of the causes of the growing number of flood catastrophes (DBU, 2002).

Reduced recycling of crop residue, minimal and unbalanced fertilizer addition, limited options for crop rotation and the regular intensive tillage are some of the factors responsible for the soil degradation over time. Tillage primarily helps in weed management and to create a seed bed with a fine soil tilth suitable for germination and seedling establishment. Additional reasons for practicing conventional tillage by manual, animal powered or mechanized means, include mineralization of nutrients, incorporation of fertilizers, crop residues and soil amendments, temporary alleviation of compaction, and management of some soil-borne diseases and insects (Hobbs et al., 2008; Kassam et al., 2009). However, regular tillage breaks down soil organic matter through mineralization, more so in warmer climates (Kirschbaum, 1995), thus contributing to deteriorating soil physical, chemical and biological properties (Wall, 2007). Tillage also adversely affects soil structure, with consequences for water infiltration and soil erosion through runoff, and create hardpans below the plough layer (Thierfelder & Wall, 2009). These adverse effects of tillage have been addressed over recent decades by the development of conservation agriculture

(CA) (Garcia-Torres et al., 2003). Conservation agriculture is defined as cropping systems based on minimal soil disturbance, permanent surface cover through crop residue retention and diverse crop rotations and associations (Hobbs et al., 2008; Kassam et al., 2009).

Soil quality is governed primarily by the tillage practices used to fulfill the contrasting soil physical and hydrological requirements of the rice and subsequent crop (Mohanty et al., 2007). Current crop cultivation practices in these systems degrade the soil and water resources thereby threatening the sustainability of the system (Fujisaka et al., 1994; Byerlee & Siddiq, 1994; Hobbs and Morris, 1996; Ali and Byerlee, 2000; Duxbury et al., 2000; Kumar and Yadav, 2001; Gupta et al., 2003; Ladha et al., 2003a). Evidence from long-term experiments shows that crop yields are stagnating and sometimes declining (Duxbury et al., 2000; Ladha et al., 2003a,b). Agricultural technologies that can save resources reduce production costs and improve production while sustaining environmental quality are therefore becoming increasingly important (Gupta et al., 2002; Hobbs & Gupta, 2003).

Soil affects not only production, but also the management of other natural resources, such as water. Soil structure is strongly correlated with the organic matter content and the soil life. Organic matter stabilizes soil aggregates, provides feed to soil life and acts as a sponge for soil water. With intensive tillage-based agriculture, the organic matter of soil is steadily decreasing, leading to a decline in productivity (Shaxon & Barber, 2003). World soils play an important role in carbon (C) cycling. Being a principal terrestrial C pool, soils contain more than twice the C than in the atmospheric, in the land plant or biotic pool. It is apparent, however, that atmospheric C pool has increased at the expense of soil pool since the beginning of agriculture. Agricultural practices with drastic impact on increasing C efflux include deforestation, burning, plowing, and continuous cropping (Houghton et al., 1983; Lal & Logan, 1995). In general, intensive cultivation or continuous cropping leads to decline in soil organic matter content (Post et al., 1990), and release of soil organic carbon (SOC) to the atmosphere. Agricultural practices affect soil C reserve by influencing at least two processes: (i) increasing rate of biomass decomposition and mineralization releasing carbon dioxide (CO_2) into the atmosphere, and (ii) exposing SOC in the soil surface to the climatic elements thereby increasing mineralization of C.

Over the past decades, extreme climatic events such as extreme precipitation as well as extended drought periods or extreme temperatures have become more frequent and stronger (Met Office, 2005). Agricultural production systems are highly vulnerable to those changes. Resource conservation technologies (RCTs) can assist in the adaptation to climate change by improving the resilience of agricultural cropping systems and hence making them less vulnerable to abnormal climatic situations. Better soil structure and higher water infiltration rates reduce the danger of flooding and erosion catastrophes after high intensity rainstorms. Yield variations by adopting combinations of RCTs in extreme years, under either dry or wet conditions, are less pronounced than under conventional agriculture (Shaxon & Barber, 2003; Bot & Benites, 2005). Conservation agriculture can also help to mitigate climate change by reducing emission of green house gases. By adopting suitable RCTs, soils can retain C from CO_2 and store it safely for long periods of time. It is becoming increasingly difficult to achieve additional gains in productivity, profit, and product quality by using the single-technology-centric approach. Therefore, a systems approach is needed to adapt to emerging challenges and to enhance the productivity, profitability, and resource-use efficiency of the system on a sustainable basis (Ladha et al., 2003, Gupta & Seth, 2007).

Resource conservation technologies in rice based cropping system

Irrigated rice is increasingly subject to (i) the high fuel costs of puddling and the reduced availability of labor, (ii) the water consumption of traditionally puddled rice is too high in many regions. Hence alternatives must be found. Also the release of greenhouse gases such as methane is high in traditionally flooded rice (Gao, 2006). Rice cultivation has therefore been adapted to conservation agriculture in several countries. Rice can be cultivated without puddling or permanent flooding by adopting RCTs. Several efforts have been done in this regard (Gupta & Seth, 2007; Humphreys & Roth, 2008). Cropping systems involving residue retention and zero tillage perform better in terms of profitability, yields and resource conservation, while conventional systems and zero tillage systems without residue retention are inferior. Most RCTs have been aiming at the two most crucial natural resources, water and soil. However, some of them would also affect the efficiency of other production resources and inputs such as labor and farm power or fertilizer. Some of the more popular RCTs, particularly in irrigated or rice based cropping systems, are the following:

Direct seeding

Direct seeding of rice compared with transplanted rice saves water as there is no puddling. There are huge savings of labor and fuel. Further, the total growing period from seed to seed is reduced by about 10 days and yields and water efficiency of the following rotation crops other than rice are increased (PDCSR, 2005). However, weed management is more difficult in dry direct-seeded rice. Direct seeding is another complement to conservation agriculture. Although transplanting of crops, including paddy rice, is possible under zero-tillage, direct seeding is preferable for the reasons mentioned above. In addition, direct seeding results in less soil movement than transplanting, which often involves some sort of strip tillage. At the same time, CA facilitates direct seeding by reducing several problems, such as surface crusting or weed control, encountered when direct seeding is applied in isolation.

Bed planting

Bed planting refers to a cropping system where the crop is grown on beds and irrigation water is applied in furrows between the beds. This is a common practice for row crops, but not for small grain crops such as wheat and rice. The advantages are saving of irrigation water, improved fertilizer efficiency, better weed control, and a reduced seed rate. The most important one as an RCT is the saving of irrigation water because of reduced evaporation surface and efficiency in distribution. In addition, the rooting environment is changed and aeration of the bed zone is better than with flat planting. Water savings compared to flat surfaces of 26% for wheat and 42% for transplanted rice have been reported, with yield increases at the same time of 6.4% for wheat and 6.2% for rice (RWC-CIMMYT, 2003). Different type of bed plantings can be used under different situations which are:

Raised-bed transplanted rice: A bed former-cum-drill seeder is used to form 37-cm-wide raised beds and 30-cm-wide furrows in well-prepared, pulverized soil. Then, 21-days old seedlings are planted on both sides of moist beds. Furrows are kept flooded for up to 21 days after transplanting.

Raised-bed drill-seeded rice: A bed former-cum-zero-till drill is used to form 37-cm-wide raised beds and 30-cm-wide furrows in well-prepared and pulverized soil, and dry rice seeds are sown in rows on both sides of moist beds. Frequent light irrigations are applied for quick germination and crop establishment. Yields of raised bed-dry-direct seeded rice were lower by 29% than conventional tilled transplanted rice (Kumar & Ladha, 2011).

Permanent (double) bed-planted rice: Drill seeding on raised beds is practiced for both rice and wheat in a sequence. It helps in good drainage, saves irrigation water and facilitates mechanical weeding. Permanent-bed-planting with double zero tillage for rice and wheat can significantly increase rice and wheat yield. Compared with the traditional cropping technique, wheat yield increased by 6.7%~9.7%, and rice yield by 5.1~6.7% (YongLu et al., 2005).

Reduced and zero tillage

Intensive soil tillage is the main cause for the reduction in soil organic matter and hence degradation of soils. Tillage accelerates the mineralization of organic matter and destroys the habitat of soil life. In addition to this, zero tillage results in water savings and improved water-use efficiency. Since the soil is not exposed through tillage, the unproductive evaporation of water decreases and water infiltration is facilitated (DBU, 2002). The possible water savings through zero tillage vary depending on the cropping system and climatic conditions and about 15–20% water saving can be expected (PDCSR, 2005). Various combinations of RCTs involving reduced tillage are as follows (Ladha et al., 2009).

Reduced-till (non puddled) transplanted rice: 2–3 dry tillages followed by planking/leveling and ponding water but without puddling; 21–30 days old seedlings are transplanted at random or in rows. Good soil structure is maintained due to reduced tillage and no puddling.

Reduced-till (non puddled) dry drill-seeded rice: Dry seeds are drilled in rows by a zero cum ferti-seed-drill at 2–3 cm depth in a well-prepared leveled and moist soil, followed by one light irrigation applied for good germination.

Reduced-till drill-seeded rice with a power tiller–operated seeder: The power tiller–operated seeder (PTOS) is a tiller with an attached seeder and a soil-compacting roller. The PTOS is used to till shallow (4–5 cm depth), sow seeds in rows at adjustable distance, and cover seed and compact the soil at the same time in a single pass.

Reduced-till (non-puddled) dry drill-seeded rice + Sesbania: Rice is drill-seeded, *Sesbania* seeds either drill-seeded or broadcast on the same day rice is sown in reduced-till plots followed by *Sesbania* knocked down at 25–30 days after sowing (DAS) with 2-4,D.

Zero-till (nonpuddled) transplanted rice: Transplanting rice seedlings in flooded field at optimum soil moisture without tillage and seedbed preparation.

Zero-till drill-seeded rice: Fields are flush-irrigated to moisten the soil and allow weeds to germinate. After about 2 weeks, glyphosate is applied to kill all weeds. A zero-till drill seeder is used to drill rice seeds at shallow depth, followed by a light irrigation to have a quick and uniform germination.

Zero-till drill-seeded rice and Sesbania: Rice is drill-seeded; *Sesbania* seeds either drill-seeded or broadcast in zero-till plots. *Sesbania* knocked down at 25–30 DAS with 2-4,D.

Double zero-till drillseeded rice: Rice is zero-till drill-seeded at optimum moisture in the presence of residues, along with need-based preplant herbicide for weed control. In winter, wheat is similarly zerotill drill-seeded in the same field. Compared with conventional tillage systems, double zero tillage consumed 12–20% less water with almost equal system productivity and demonstrated higher water productivity in rice wheat system (Jat et al., 2009).

Mulching and green manuring

The supply of organic matter to the soil through mulching and green manure is an important factor for maintaining and enhancing soil fertility. The mulching material can result from crop residues or green manure crops. This provides feed for the soil life and mineral nutrients for plants. If legume crops are used as green manure, they can supply up to 200 kg ha^{-1} nitrogen to the soil. This can result in savings of 50–75% mineral fertilizer for rice (RWC-CIMMYT, 2003). Left on the soil surface, the mulch reduces evaporation, saves water, protects soil from wind and water erosion, and suppresses weed growth.

Crop residue burning is a problem, particularly rice straw after combine harvesting in the north-west Indo-Gangetic Plain (Ladha et al., 2003). The development of zero-till drill seeding of wheat and rice under crop residue mulch provides an option to reduce residue burning, thereby reducing greenhouse gas emissions (Iqbal & Goheer, 2008). A soil amendment with residue may also improve soil quality.

Inclusion of grain legumes, green-manure crops, or *Sesbania* can add some biologically fixed N (BNF) and organic matter to soils, thereby building up soil fertility in the long run (Peoples et al., 1995, Ladha et al., 1996). Simultaneous sowing of rice and *Sesbania* and killing of young *Sesbania* plants at 30–45 days after sowing by selective herbicides (commonly referred to as brown manuring) could help build up soil fertility in the RW system (Singh et al., 2007).

Laser-assisted land leveling

For surface-irrigated areas, a properly leveled surface with the required inclination according to the irrigation method is absolutely essential. Traditional farmers' methods for leveling by eyesight, particularly on larger plots, are not accurate enough and lead to extended irrigation times, unnecessary water consumption, and inefficient water use. With laser leveling, the unevenness of the field is reduced to about ± 2 cm, resulting in better water application and distribution efficiency, improved water productivity, better fertilizer efficiency, and reduced weed pressure. Water savings of up to 50% have been reported in wheat and 68% in rice (Jat et al., 2006).

Controlled traffic farming

Controlled traffic farming restricts any traffic in the field always to the same tracks. Although these tracks are heavily compacted, the rooting zone never receives any compaction, resulting in better soil structure and higher yields. Through border effects, the area lost in the traffic zones is easily compensated for by better growth of plants adjacent to the tracks so that overall yields are usually higher than in conventional systems with random traffic (Kerr, 2001). Obviously, controlled traffic farming is the ideal complement to zero-tillage or bed-planting systems.

Sustainable and resource-conserving crop management technologies offer several major benefits under changing climate. These include:

1. Practices such as reduced tillage in combination with crop residue retention can buffer crops against severe climatic events, for example, by increasing water harvest and thereby offsetting water shortages that will intensify as global temperatures rise.
2. Improving the overall environment for root growth, such practices permit the genetic potential of improved cultivars to be more optimally expressed helping to close yield gaps that may already exist.
3. Diversification of cropping systems helps to control soil borne diseases.

Resource conservation technologies and greenhouse gases emissions

Inter governmental Panel on Climate Change (1995) estimated that 20% of the greenhouse effect is related to agricultural activities. Therefore, the management of soil resources, in general, and that of the SOC, in particular, is extremely important. Soil resources of the world may be the key factor in the creation of an effective carbon sink and mitigation of the greenhouse effect.

Conservation agriculture helps to mitigate the effects of climate change, by sequestering soil organic carbon and reducing emission of greenhouse gases (GHGs). With the increasing soil organic matter, soils under CA can retain carbon from carbon dioxide and store it safely for long periods of time. This carbon sequestration continues for 25 to 50 years before reaching a new plateau of saturation (Reicosky, 2001). The consumption of fossil fuel for agricultural production is significantly reduced under CA and burning of crop residues is completely eliminated, which also contributes to a reduction in greenhouse gas release. Depending on the type of management, soils under zero tillage might also emit less nitrous oxide (Izaurralde, 2004). With paddy rice in particular, the change to zero tillage systems combined with adequate water management can positively influence the release of other greenhouse gases, such as methane and nitrous oxides (Belder, 2005; Gao, 2006).

Carbon dioxide emission: Atmospheric CO_2 concentration is increasing at the rate of 5% a year. Burning fuel and changing land use are two major human activities that result in this increase (Lal & Kimbel, 1995). Organic carbon in the soil is the main source of GHG emissions from the soil (Post & Kwon, 2000). In rice based agricultural lands, organic carbon is supplied to the soil as root exudates, dead roots and stubble of crops. Some other additional organic carbon is also supplied by organic matter incorporation (Nishimura et al., 2008). The amount of organic carbon stored in paddy soils is greater than in upland soils because of different biochemical processes and mechanisms specifically caused by the presence of flooded water in paddy soils (Liping & Erda, 2001). The dynamics of carbon in paddy fields significantly differs from that in fields with upland crop cultivation in which the aerobic decomposition process is dominant. During the submerged period of paddy rice cultivation, CO_2 production in the soil is severely restricted under anaerobic conditions. Chen et al. (2001) has reported continuous rice cultivation has a tendency to increase CO_2 emission from soil. On the other hand, researchers also reported that paddy field acts as net sink of atmospheric CO_2 (Yin et al., 2008). Liu et al (2007) has reported that the optimum/high moisture condition in the paddy fields reduces the CO_2 flux by increasing the gross primary productivity (GPP) over net ecosystem respiration (NER).

Nitrous oxide emission: Nitrous oxide (N_2O) is an important greenhouse gas, accounting for about 5% of total global warming (Robertson et al., 2000). The emission of N_2O occurs as a result of nitrification and denitrification processes occurring in aerobic and anaerobic soil conditions, respectively. Total emissions of N_2O-N were lower (0.002 kg ha^{-1}) under continuous submergence than under alternate wetting and drying (0.050 to 0.054 kg ha^{-1}). Over a period of 12 days, approximately 0.12% of applied N was emitted as N_2O from soil under alternate wetting and drying (AWD), whereas this value was negligible under continuous submergence (Mohanty et al., 2009). Thus, growing rice in unpuddled soil under aerobic conditions will have implications for the emission of GHG N_2O (Pathak et al., 2007). However, emissions of methane (CH_4), another greenhouse gas, are less under aerobic conditions than under flooded rice cultivation (Gupta-Vandana et al., 2009). In rice, it has been observed that strategies to reduce emissions of N_2O often lead to an increase in emissions of CH_4. There is tradeoff between these two gases. Both of these gases have different global warming potential (GWP), hence the RCTs with lesser GWP need to be recommended for rice based systems.

Methane emission: The regional distribution of the rice–wheat system warrants a comparative assessment of CH_4 emissions in Central China and Northern India, because these two regions collectively account for more than 75% of the global rice–wheat area. The available CH_4 emission records from rice fields in Central China showed a relatively high background level of CH_4 emissions ranging from 200 to 900 kg CH_4 ha^{-1} under mineral fertilization (Zheng et al., 1997; Wassmann et al., 1993) and up to 1100 kg CH_4 ha^{-1} following organic amendments (Khalil et al., 1998). Emission records from Northern India were consistently lower and did not exceed 30 kg CH_4 ha^{-1} under mineral fertilization (Mitra et al., 1999) and 50 kg CH_4 ha^{-1} under organic treatment (Debnath et al., 1996). Methane is mainly generated from organic material that is recently formed or added during the growing season of the rice itself. Moreover, the post-wheat fallow period until the transplanting of rice crop should result in converging soil conditions. Wheat straw only slightly deviates from rice straw in its C content, so that an impact deriving from distinct residues is rather unlikely even under high doses of straw application. The composition of organic residues, however, could become a factor when rice–wheat system is compared to rice–legume rotations. In rice fields applied with residues from the preceding season, CH_4 emissions were reduced by approximately 50% when cowpea was grown instead of wheat (Abao et al., 2000).

Resource conservation technologies to enhance carbon sequestration

Resource conservation technologies involving no or minimum tillage with direct seeding, bed planting and crop residue management are now being advocated as alternatives to the conventional rice based cropping system for improving the input-use efficiency, productivity, and sustainability of the system (Gupta et al., 2003, Bhushan et al., 2007). The SOC content depends on the type of conservation tillage and amount of crop residues returned to the soil surface, and may be linearly related to crop residue returned to the soil. Crop residues produced in the world are estimated at 2962 million Mg yr^{-1}. Even a fraction of these residues returned to the soil through conservation tillage can increase SOC content and lead to C sequestration.

Tillage effects on soil organic matter: While thorough tillage of the soil has immediate advantages for controlling weeds and creation of a fine soil tilth for sowing seed and for seedling emergence, there are adverse consequences of regular tillage on soil quality which become more apparent over the longer term. Soil quality is largely determined by soil organic matter (SOM) status and there is much accumulated evidence in temperate and tropical soils of declining SOM with tillage as compared to relatively undisturbed soil (Ogle et al., 2005). There is a range of soil physical, chemical and biological consequences to declining SOM caused by tillage. A decline in SOM reduces soil particle aggregation (Chaney & Swift, 1984), which slows water infiltration (Thierfelder & Wall, 2010), reduces aeration and increases bulk density, thereby restricting root distribution and function. With reduced SOM, soil water holding capacity is decreased and susceptibility to water erosion increased through increased runoff (Thierfelder & Wall, 2010). Declining SOM also diminishes the ability of the soil to release nutrients in approximate synchrony with crop demand (Drinkwater & Snapp, 2007). Soil organic matter provides exchange sites for nutrient ions, minimizing their leaching or sorption on clay minerals, but increases their availability for plant uptake through slow release to the soil solution. A decline in SOM results in an inevitable decline in soil biological activity (Soon & Arshad, 2005). Depending on soil type, frequent tillage may cause the development of a hardpan at the bottom of the ploughed or hoe cultivated layer which can impede water infiltration and root penetration (Thierfelder & Wall, 2009).

Conservation tillage and carbon cycling: Conservation tillage, a generic term denoting a range of tillage practices that reduce soil and water losses in comparison with conventional or plow-based tillage method and use crop residue mulch to provide a protection against raindrop impact, increases SOC through enhancement of soil aggrading processes and reversal of soil degrading processes (Lal, 1989; Carter, 1993). The SOC content also depends on the type of conservation tillage and amount of crop residues returned to the soil. Several experiments conducted in temperate and tropical regions have demonstrated the beneficial effects of conservation tillage on SOC (Juo and Lal, 1978; Lal, 1979; Dalal, 1989; 1992; Lal et al., 1989; Carter, 1993). On an Ultisol in Eastern Nigeria, Ohiri and Ezumah (1990) observed about 8% higher SOC in conservation tillage compared with conventional tillage systems. Conservation tillage is known to enhance SOC in the surface soil horizons through several mechanisms (e.g., alterations of soil temperature and moisture regimes, and erosion control) (Lal, 1989; Kern & Johnson, 1993).

Crop residue and its role in soil organic carbon management: Crop residue management, quantity and quality of biomass applied to the soil, has a significant impact on soil quality and resilience, agronomic productivity, and carbon sequestration. Crop residue is an important and a renewable resource. Developing techniques for effective utilization of this vast resource is a major challenge. Improper use of crop residues (e.g. removal and burning) can accelerate erosion, deplete soil fertility, and pollute environment through burning and eutrophication of surface and contamination of groundwater. If managed properly, residue management may save energy, recycle nutrients, enhance soil fertility, improve soil structure and sequester carbon.

The quantity of crop residue produced depends on the arable land area, crops and cropping systems, and soil and crop management. The global arable land area is about 1.4 billion ha with about 31% in Asia (FAO, 1993). Based on the mean residue:grain ratio for different crops, annual production of crop residue is estimated at 3.4 Pg in the world (Lal, 1997). The amount of residue produced by cereals is usually high because of a high straw:grain ratio, low decomposition rate, and high C:N ratio. Residue production by all grain cereals is estimated at 2.5 Pg for the world. Assuming the mean carbon content of 45%, total carbon assimilated annually in the crop residue is about 1.5 Pg in the world. If 15% of the carbon assimilated in the residue can be converted to humus fraction, it may lead to carbon sequestration at the rate of 0.2 Pg yr^{-1} or 5.0 Pg of cumulative C sequestration in the world by the year 2020. Application of 50% NPK + 50% N through FYM in rice and 100% NPK in wheat, sequestered 0.39 to 0.62 Mg C ha^{-1} yr^{-1} over control (no N–P–K fertilizers or organics) in IGP of India (Nayak et al., 2012). Application of NPK either through inorganic fertilizers or through combination of inorganic fertilizer and organics such as farm yard manure or crop residue or green manure improved the SOC, particulate organic carbon, microbial biomass carbon concentration and their sequestration rate.

Conclusions

Locally adopted RCTs appropriate to resource endowments of farmers and the biophysical environment hold potential to improve management of natural resources and provide sustainable increases in productivity. The long-term trials, set up at the beginning of the green revolution era to understand nutrient mining in the system and to develop nutrient management strategies have provided valuable information to develop future strategies. Appropriate long-term monitoring must continue, and be relevant to future changes in tillage and water management practices. In addition, benefits of changes in the tillage system and stubble management to the soil ecosystem need to be better understood. Zero-till, permanent bed-planting systems and new nonpuddled rice establishment techniques coupled with laser land levelling can go a long way to increasing the use efficiency of these vital natural resources. Resource conservation technologies applied in isolation have advantages and disadvantages. They are not universally applicable as the problems can sometimes outweigh the benefits. However, by combining different resource conservation technologies, synergies can be created to eliminate the disadvantages of single technologies and accumulate the benefits. Different RCTs are successfully applied under the concept of conservation agriculture in different cropping systems around the world, allowing stable agricultural production without the known negative environmental impact.

Mitigation options in the rice based cropping system may individually be of limited scope, but they may achieve a discernable composite effect when implemented in coordinated fashion. Mitigation programs will rely on win–win opportunities when emissions can be reduced with another concomitant benefit such as higher yields, less fertilizer, water needs, etc. Targeting one individual gas alone seems inappropriate due to tradeoff effects in the emissions of CH_4, N_2O, and CO_2. More research is needed to combine geographic information, emission models, yield models and socio-economic information to devise site-specific packages of mitigation technologies.

References

Abao, E.B. Jr., Bronson, K.F., Wassmann, R., & Singh, U. (2000). Simultaneous records of methane and nitrous oxide emissions in rice-based cropping systems under rain fed conditions. *Nutrient Cycling in Agroecosystems,* 58, 131-139.

Ali, M., & Byerlee, D. (2000). Productivity growth and resource degradation in Pakistan's Punjab: A decomposition analysis. *Policy Economics Working Paper*, World Bank.

Aulakh, K.S. (2005). *Punjab Agricultural University, accomplishments and challenges*. Ludhiana. p.23.

Belder, P. (2005). Water saving in lowland rice production: An experimental and modelling study. Wageningen University, Netherlands. (Ph.D. thesis with English and Dutch summaries).

Bhushan, L., Ladha, J.K., Gupta, R.K., Singh, S., Tirol-Padre, A., Saharawat, Y.S., Gathala, M., & Pathak, H. (2007). Saving of water and labor in rice-wheat system with no-tillage and direct-seeding technologies. *Agronomy Journal,* 99, 1288-1296.

Bot, A., & Benites, J. (2005). The importance of soil organic matter, key to drought-resistant soil and sustained food production. *FAO Soils Bulletin* 80. Rome (Italy): FAO.

Byerlee, D. & Siddiq, A. (1994). Has the green revolution been sustained? The quantitative impacts of the seed-fertilizer technology in Pakistan revisited. *World Development*, 22(9), 1345-1361.

Carter, M.R. (Ed.). (1993). *Conservation tillage in temperate agroecosystems*. (pp. 390). Boca Raton, Fl: Lewis Publishers.

Chaney, K., & Swift, R.S. (1984). The influence of organic matter on aggregate stability in some British soils. *J.Soil Sci.,* 37, 329-335.

Chen, H.W., Yen, J.H., Chung, R.S., Lai, C.M., Yang, S.S., & Wang, S.S. (2001). Carbon dioxide flux densities in cultivated rice paddy fields. *Proceedings of the National Science Council, Republic of China,* 25(4), 239-247.

Dalal, R.C. (1989). Long-term effects of no-tillage, crop residue and nitrogen application on properties of a *vertisol*. *Soil Science Society of America Journal,* 53, 1511-1515.

Dalal, R.C. (1992). Long-term trends in total nitrogen of a *vertisol* subjected to zero-tillage, nitrogen application and stubble retention. *Australian Journal of Soil Research,* 30, 223-231.

DBU. (2002). Innovativer Ansatz eines vorbeugenden Hochwasserschutzes durch dezentrale Maßnahmen im Bereich der Siedlungswassserwirtschaft sowei der Landwirtschaft im Einzugsgebiet der Lausitzer Neiße. Project report DBU-project AZ 15877, Deutsche Bundesstiftung Umwelt (German Federal Environment Foundation), Osnabrück, Germany.

Debnath, G., Jain, M.C., Kumar, S., Sarkar, K., & Sinha, S.K. (1996). Methane emissions from rice fields amended with biogas slurry and farm yard manure. *Climatic Change,* 33, 97-109.

Drinkwater, L.E., & Snapp, S.S. (2007). Nutrients in agroecosystems: Re-thinking the management paradigm. *Advances in Agronomy,* 92, 163-186.

Duxbury, J.M., Abrol, I.P., Gupta, R.K., & Bronson, K.F. (2000). Summary analysis of long-term soil fertility experiments with rice-wheat rotations in South Asia. In I.P. Abrol et al (Eds.), *Long-term soil fertility experiments in rice-wheat cropping systems.* New Delhi, India: Rice-wheat consortium for the Indo-Gangetic Plains.

FAO. (1993). *Production yearbook*. (pp. 254). Rome, Italy: FAO.

FAO. (2002). *Agriculture: Towards 2015/2030*. (p.420). Rome, Italy: FAO.

Fujisaka, S., Harrington, L.W., & Hobbs, P.R. (1994). Rice-wheat in South Asia: System and long-term priorities established through diagnostic research. *Agricultural Systems,* 46, 169-187.

Gao Huanwen. (2006). *The impact of conservation agriculture on soil emissions of nitrous oxide*. Draft report. Beijing, China: Asian and Pacific Centre for Agricultural Engineering and Machinery.

Garcia-Torres, L., Benites, J., Martinez-Vilela, A., Holgado-Cabrera, A. (Eds.). (2003). *Conservation agriculture: Environment, farmers experiences, innovations, socio-economy, policy*. Dordrecht, The Netherlands; Boston, Germany; London, UK: Kluwer Academia Publishers.

Gupta, R.K., & Seth, A. (2007). A review of resource conserving technologies for sustainable management of the rice–wheat cropping systems of the Indo-Gangetic plains (IGP). *Crop protection,* 26, 436-447.

Gupta, R.K. et al. (2003). In J.K. Ladha et al. (Eds.), *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication No. 65. (pp. 1-25). Madison, Wisconsin, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Gupta, R.K., & Rickman, J. (2002). Design improvements in existing zero-till machines for residue conditions. Traveling Seminar Report Series 3. New Delhi, India: Rice-Wheat Consortium for the Indo- Gangetic Plains.

Gupta-Vandana, Singh, S., Chandna Parvesh, Tewari, A., Kumar, K., Ladha, J.K., Gupta, R.K., & Gupta, P.K. (2009). Mitigating methane emission in rice with resource conserving technologies. In *Conservation agriculture: Innovations for improving efficiency, equity and environment.* Proceedings of 4th World Congress on Conservation Agriculture, 4-7 February 2009. New Delhi, India: Indian Council of Agriculture Research.

Hobbs, P.R., Sayre, K., & Gupta, R. (2008). The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B,* 363(1491), 543-555.

Hobbs, P.R., & Morris, M. (1996). Meeting South Asia's future food requirements from rice-wheat cropping systems: Priority issues facing researchers in the post green revolution era. NRG paper 96-01. CIMMYT, Mexico.

Hobbs, P.R., & Gupta, R.K. (2003). Rice-wheat cropping systems in the Indo-Gangetic Plains: Issues of water productivity in relation to new resource-conserving technologies. In J.W. Kijne, R. Barker, D. Molden (Eds.), *Water productivity in agriculture: Limits and opportunities for improvement.* Wallingford, UK: CABI Publications.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R., & Woodwell, G.M. (1983). Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere. *Ecological Monographs,* 53, 235-262.

Humphreys, E., Roth, C.H. (Eds.). (2008). Proceedings of the workshop on permanent beds and rice-residue management for rice–wheat systems in the Indo-Gangetic Plains, Ludhiana, India, September 7–9, 2006. ACIAR No. 127. Australian Centre for International Agricultural Research, Canberra, Australia, in press.

Intergovernmental Panel on Climate Change. (1995). Agricultural options for mitigation of greenhouse gas emissions. IPCC Workgroup II, Chapter 23, Washington, D.C.

Iqbal Mohsin, M., & Goheer Arif, A. (2008). Greenhouse gas emissions from agro-ecosystems and their contribution to environmental change in the Indus basin of Pakistan. *Advances in Atmospheric Sciences,* 25(6), 71.

Izaurralde, R.C., Lemke, R.L., Goddard, T.W., McConkey, B., & Zhang, Z. (2004). Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Science Society of America Journal,* 68, 1285-1294.

Jat, M.L., Chandna, P., Gupta, R., Sharma, S.K., & Gill, M.A. (2006). Laser land levelling: A precursor technology for resource conservation. Rice-Wheat Consortium Technical Bulletin Series 7. (p. 48). New Delhi, India: Rice-Wheat Consortium for the Indo Gangetic Plains.

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, Vipin., Sharma, S.K., Kumar, V., & Gupta, R. (2009). Evaluation of precision land leveling and double zero-till systems in the rice–wheat rotation: Water use, productivity, profitability and soil physical properties. *Soil and Tillage Research*, 105(1), 112-121.

Juo, A.S.R., & Lal, R. (1978). Nutrient profile in a tropical *alfisol* under conventional and no-till systems. *Soil Science,* 127, 168-173.

Kassam, A.H. (2009). Sustainability of farming in Europe: Is there a role for conservation agriculture? *Journal of Farm Management,* 10, 717-728.

Kern, J.S., & Johnson, M.G. (1993). Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal*, 57, 200-210.

Kerr, P. (2001). Controlled traffic farming at the farm level. GRDC Research Update, Finley NSW, Australia.

Khalil, M.A.K., Rasmussen, R.A., Shearer, M.J., Chen, Z.L., Yao, H., & Yang, J. (1998). Emissions of methane, nitrous oxide, and other trace gases from rice fields in China. *Journal Geophysical Research - Atmosphere,* 103, 25241-25250.

Kirschbaum, M.U.F. (1995). The temperature dependence of soil organic matter decomposition and the effect of global warming on soil organic carbon storage. *Soil Biology and Biochemistry*, 27, 753-760.

Kumar Virender & Ladha, J.K. (2011). Direct seeding of rice: Recent developments and future research needs. *Advances in Agronomy*, 111, 297-413.

Kumar, A., & Yadav, D.S. (2001). Long-term effects of fertilizers on the soil fertility and productivity of a rice-wheat system. *Journal of Agronomy and Crop Science,* 86, 47-54.

Ladha, J.K., Kundu, D.K., Angelo-Van Coppenolle, M.G., Carangal, V.R., Peoples, M.B., Dart, P.J. (1996). Legume productivity and soil nitrogen dynamics in lowland rice-based cropping systems. *Soil Science Society of America Journal*, 60, 183-192.

Ladha, J.K., Kumar, V., Alam, M.M., Sharma, S., Gathala, M., Chandna, P., Saharawat, Y.S., & Balasubramanian, V. (2009). Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In J.K. Ladha, Y. Singh, O. Erenstein, B. Hardy (Eds.), *Integrated crop and resource management in the rice–wheat system of South Asia.* (pp. 69-108). Los Banos, Philippines: International Rice Research Institute.

Ladha, J.K., Dawe, D., Pathak, H., Padre, A.T., Yadav, R.L., Bijay-Singh, Yadvinder Singh, Singh, Y., Singh, P., Kundu, A.L., Sakal, R., Ram, N., Regmi, A.P., Gami, S.K., Bhandari, A.L., Amin, R., Yadav, C.R., Bhattarai, E.M., Das, S., Aggarwal, H.P., Gupta, R.K., & Hobbs, P.R. (2003a). How extensive are yield declines in long-term rice-wheat experiments in Asia?. *Field Crops Research*, 81, 159-180.

Ladha, J.K., Pathak, H., Padre, A.T., Dawe, D., & Gupta, R.K. (2003b). Productivity trends in intensive rice-wheat cropping systems in Asia. In J.K. Ladha, J.E. Hill, J.M. Duxbury, Raj K. Gupta, R.J. Buresh (Eds.), *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication 65. (pp. 45-76). Madison, USA: ASA-CSSA-SSSA.

Ladha, J.K., Hill, J.E., Duxbury, J.D., Gupta, R.K., Buresh, R.J. (Eds.). (2003). *Improving the productivity and sustainability of rice-wheat systems: Issues and impact*. ASA Special Publication 65. (p. 211). Madison, USA: ASA-CSSA-SSSA.

Lal, R. (1997). Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO_2-enrichment. *Soil and Tillage Research*, 43, 81-107.

Lal, R., & Logan, T.J. (1995). Agricultural activities and greenhouse gas emissions from soils of the Tropics. In R. Lal, J. Kimble, E.Levine, B.A. Stewart (Eds.), *Soil management and greenhouse effect.* (pp. 293-307). Boca Raton, Fl: CRC/Lewis Publishers.

Lal, R. (1979). Influence of six years of no-tillage and conventional plowing on fertilizer response of maize on an *alfisol* in the Tropics. *Soil Science Society of America Journal*, 43, 399-403.

Lal, R. (1989). Conservation tillage for sustainable agriculture: Tropics vs. Temperate environments. *Advances in Agronomy*, 42, 85-197.

Lal, R., & Kimble, J. (1995). Soils and global change. In *Advances in Soil Sciences* (1th ed.). (pp. 1-2). FL Boca Raton, USA: CRC Press.

Liping, G., & Erda, L. (2001). Carbon sink in cropland soils and the emission of greenhouse gasses from paddy soils: A review of work in China. *Chemosphere-Global Change Science*, 3, 413-461.

Liu, H., Zhao, P., Sun, G.C., Lin, Y.B., Rao, X.Q., & Wang, Y.S. (2007). Characteristics of CO_2, CH_4 and N_2O emission from winter fallowed paddy soils in hilly areas of South China. *Ying Yong Sheng Tai Xue Bao* (in Chinese), 18, 57-62.

Met Office. (2005). *Climate change, rivers and rainfall*. Recent research on climate change science from the Hadley Centre, Exeter, UK.

Mitra, S., Jain, M.C., Kumar, S., Bandyopadhyay, S.K., & Kalra, N. (1999). Effect of rice cultivars on methane emission. *Agriculture Ecosystems Environment*, 73, 177-183.

Mohanty, M., Painuli, D.K., Misra, A.K., & Ghosh, P.K. (2007). Soil quality effects of tillage and residue under rice–wheat cropping on a *vertisol* in India. *Soil and Tillage Research*, 92, 243-250.

Mohanty, S., Ladha, J.K., Gathala, M., Pathak, H., Jain, N., & Sharma, S. (2009). Emission of N_2O from soil with different resource conserving technologies. In *Conservation agriculture: Innovations for improving efficiency, equity and environment*. Proceedings of the 4th World Congress on Conservation Agriculture, 4-7 February 2009. New Delhi (India): Indian Council of Agricultural Research.

Nayak, A.K., Gangwar, B., Shukla, A.K., Mazumdar Sonali, P., Kumar, Anjani., Raja, R., Kumar, Anil., Kumar, Vinod., Rai, P.K., & Mohan, Udit. (2012). Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. *Field Crops Research*, 127, 129-139.

Nishimura, S., Yonemura, S., Sawamoto, T., Shirato, Y., Akiyama, H., Sudo, S., & Yagi, K. (2008). Effect of land use change from paddy rice cultivation to upland crop cultivation on soil carbon budget of a cropland in Japan. *Agriculture, Ecosystems and Environment*, 125, 9-20.

Ogle, S.M., Breidt, F.J., & Paustian, K. (2005). Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. *Biogeochemistry*, 72, 87-121.

Ohiri, A.C., & Ezumah, H.C. (1990). Tillage effects on cassava production and some soil properties. *Soil and Tillage Research,* 17, 221-229.

Pathak, H., Ladha, J.K., Saharawat, Y.S., & Gathala, M. (2007). Impact, productivity, income and environmental impact assessment of RCTs in RW system using modeling tool. In Proceedings of the 94th Indian Science Congress, 3-7 January 2007, Chidambaram, India. p. 32.

PDCSR. (2005). Annual report 2004-05. (p.143). Modipuram, Meerut, India: Project Directorate for Cropping Systems Research.

Peoples, M.B., Herridge, D.F., & Ladha, J.K. (1995). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant Soil,* 174, 3-28.

Post, W.M., Peng, T.H., Emaniel, W.R., King, A.W., Dale, V.H., & DeAngelis, D.I. (1990). The global carbon cycle. *American Scientist,* 78, 310-326.

Post, W.M., & Kwon, K.C. (2000). Soil carbon sequestration and land use change: Processes and potential. *Global Change Biology,* 6, 317-327.

Reicosky, D. (2001). Conservation Agriculture: Global environmental benefits of soil carbon management. In L. Garcia-Torres, J. Benites, A. Martínez-Vilela (Eds.), *Conservation Agriculture - A Worldwide Challenge*. (p. 3-12).

Robertson, G.P., Paul, E.A., & Harwood, R.R. (2000). Greenhouse gases in intensive agriculture: Contribution of individual gases to the radiative forcing of the atmosphere. *Science,* 289, 1922-1925.

RWC-CIMMYT. (2003). Addressing resource conservation issues in rice-wheat systems of South Asia: A resource book. (p. 305). New Delhi, India: Rice-Wheat Consortium for the Indo-Gangetic Plains/ International Maize and Wheat Improvement Centre.

Shaxon, T.F., & Barber, R.G. (2003). Optimizing soil moisture for plant production: The significance of soil porosity. *FAO Soils Bulletin* No. 79. Rome, Italy: FAO.

Singh, S., Ladha, J.K., Gupta, R.K., Bhushan, L., Rao, A.N., Sivaprasad, B., & Singh, P.P. (2007). Evaluation of mulching, intercropping with *Sesbania* and herbicide use for weed management in dry-seeded rice (*Oryza sativa* L.). *Crop Protection,* 26, 518-524.

Soon, Y.K., & Arshad, M.A. (2005). Tillage and liming effects on crop and labile soil nitrogen in an acid soil. *Soil and Tillage Research*, 80, 23-33.

Thierfelder, C., & Wall, P.C. (2009). Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research,* 105, 217-227.

Thierfelder, C., & Wall, P.C. (2010). Investigating Conservation Agriculture (CA) systems in Zambia and Zimbabwe to mitigate future effects of climate change. *Journal of Crop Improvement,* 24, 113-121.

Wall, P.C. (2007). Tailoring conservation agriculture to the needs of small farmers in developing countries: An analysis of issues. *Journal of Crop Improvement,* 19, 137-155.

Wassmann, R., Sch¨utz, H., Papen, H., Rennenberg, H., Seiler, W., Dai, A.G., Shen, R.X., Shangguan, X.J., & Wang, M.X. (1993). Quantification of methane emissions from Chinese rice fields (Zhejiang Province) as influenced by fertilizer treatment. *Biogeochemistry,* 11, 83-101.

Yin, C.M., Xie, X.L., & Wang, K.R. (2008). Effect of straw mulching on CO_2 flux on winter fallow paddy field. *Ying Yong Sheng Tai Xue Bao* (in Chinese), 19, 115-119.

YongLu, T., JiaGuo, Z., & Gang, H. (2005). Studies on permanent-bed-planting with double zero tillage for rice and wheat in Sichuan basin. *Southwest China Journal of Agricultural Sciences,* 18(1), 25-28.

Zheng, X.H., Wang, M.X., Wang, Y.S., Heyer, J., Kogge, M., Papen, H., Jin, J.S., & Li, L.T. (1997). N_2O and CH_4 emissions from rice paddies in Southeast China. *Chinese Journal of Atmospheric Sciences,* 21, 167-174.

*****

Chapter 12

Management strategies for improving nitrogen use efficiency in rice based system under various rice ecologies

A.K. Shukla[1*], A.K. Nayak[2], R. Raja[2], Mohammad Shahid[2] and B.B. Panda[2]
[1]Indian Institute of Soil Science, Bhopal, Madhya Pradesh, India
[2]Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: arvindshukla2k3@yahoo.co.in

The impact of modern agriculture on natural resources has become a major global concern. Aiming at improving resource-use efficiencies, in high-input systems the focus should be on more yield with less fertilizer nitrogen (N). In low-input systems additional use of N fertilizer may be required to increase yield level and yield stability. In order to achieve a higher agronomic nitrogen use efficiency (NUE), it is inevitable that N supply should match N demand in time and space, not only for single crops but for a crop rotation as an integrated system. Nitrogen is the most important mineral nutrient for cereal production, and an adequate supply is essential for high yields, especially with modern cultivars in many agro ecosystems including rainfed and irrigated rice-based systems (Spiertz, 2010). External N application is critical for intensive rice production as appropriate N inputs enhance soil fertility, sustainable agriculture, food security (enough calories) and nutrition security (appropriate supply of all essential nutrients, including protein). High grain yields can only be obtained when rice crop assimilates adequate amounts of N in the course of growing season (Shukla et al., 2004). Although di-nitrogen gas (N_2) is the most abundant component of the earth's atmosphere, it can not be used directly by plants, with the exception of some plant species (e.g. legumes) that have developed symbiotic systems with N_2-fixing bacteria. Owing to the strong bond between its two N atoms, N_2 is almost inert and thus non-reactive. It requires a high energy input to convert N_2 into plant available, reactive N forms. By contrast, reactive nitrogen (Nr) species, such as NH_3, NH_4^+, NO_x, HNO_3, NO_3^-, N_2O and organic N forms, exist only in small quantities under natural environmental conditions (Galloway et al., 2008). The growing complexity of managing N in sustainable agricultural systems calls for problem-oriented, interdisciplinary research. A major point of concern for many intensively managed agricultural systems with high external inputs is the low resource-use efficiency, especially for N. A high input combined with a low efficiency ultimately results in environmental problems such as soil degradation, eutrophication, pollution of groundwater, and emission of ammonia and greenhouse gases. Evidently, there is a need for a transition of current agricultural systems into highly resource-use efficient systems that are profitable, but at the same time ecologically safe and socially acceptable. Here, opportunities to improve NUE in various rice ecologies are analyzed and discussed.

Rice ecologies

The importance of rice in global concerns regarding food security, poverty alleviation, preserving cultural heritage, and sustainable development has been understood very well. More than 90% of the world's rice is grown and consumed in Asia. Between now and 2020, about 1.2 billion new rice consumers will be added in Asia. Feeding these people will require the greatest effort in the history of agriculture, especially rice production. In Asia, rice is grown in 135 m ha with an annual production of 516 m t. Rice area covered by rainfed lowland and flood prone ecosystem are the most unfavorable rice ecosystem is about 35%, which is next to irrigated ecosystem (55%). The average productivity in rainfed lowland and flood-prone ecosystem is very low (1.5 – 2.8 t ha^{-1}) as compared to the irrigated ecosystem (4.9 t ha^{-1}).

Of the total rice area in India, 43.8% is irrigated, 14.6% is upland, 30.1% is rainfed lowland and 11.4% is flood-prone. In general, rice yield is very low in rainfed lowland and flood-prone ecosystem as compared to irrigated ecosystem. Rice productivity in different ecosystems are 3.6, 0.8, 2.4 and 1.5 t ha^{-1}, respectively.

Each system is different from the other with respect to varieties grown, methods of cultivation and soil and water management practices followed**.** Irrigated rice is grown in bunded fields with ensured irrigation for one or more crops a year; so that 5–10 cm of water can be maintained in the field. Rainfed lowland rice is grown in bunded fields that are flooded with rainwater for at least part of the cropping season. Rainfed rice environments experience multiple abiotic stresses and high uncertainty in timing, duration, and intensity of rainfall. Because of the environment prevailed, the farmers rarely apply fertilizer to the rice crop. Rainfed upland rice is grown under dryland mostly under direct seeded conditions. Upland environments are highly variable with respect to climate, soils type, and topography. Since rice production systems vary widely in their macro and micro environment, each system has its unique effect on carbon nitrogen dynamics in soil-plant-atmosphere continuum and hence there is wide spread variation in N loss from the system. Irrigated rice consumes about 8 to 9 m t of fertilizer N annually, which is about 10% of total N production in the world. In general most of the N applied to rice crop is lost through various mechanisms like volatilization, denitrification and leaching. Hence, rice systems are a major contributor to the accumulation of Nr compounds in the environment.

The nitrogen cycle

The N cycle refers to the circulation of N compounds through the Earth's atmosphere, hydrosphere, biosphere and pedosphere. At various points in this cycle, Nr compounds become involved in processes that can affect human health and the environment in both positive and negative ways. Nitrogen moves from the soil to the plant, and back from the plant to the soil, often with animals or humans as intermediates. The real situation is however more complex as N compounds undergo a number of transformations in the soil (mineralization, immobilization, nitrification and denitrification) and are exchanged between soil and the atmosphere (through volatilization, denitrification, biological N fixation, atmospheric deposition) and between soil and the hydrosphere (through leaching, erosion/runoff, irrigation). These transformations and fluxes constitute the soil N cycle. In 1995-96, 10.8 Tg N was applied as nitrogenous fertilizers to agricultural soils in India; another 1.14-1.18 Tg N was added through biological nitrogen fixation. Velmurugan et al. (2008) estimated the soil N pool other than forest to be as large as 1046 to 2581 Tg N. The proportion of N contained in soil which is actively recycled in the soil-plant system is not known with certainty. Crude estimates show that Indian agricultural systems produce annual harvest that removes ~4.13 Tg N from the total crop N pool of ~12.47 Tg N. Further, ~1.9 Tg N is removed from the crop N pool and used for fuel, which in turn released N_2O into atmosphere. The nitrogen contained in plants was either recycled or was supplied to consumers such as animals (~5.81 Tg N) or people (~0.57 Tg N). India has the largest livestock population in the world and the livestock biomass N pool was estimated to be ~1.62 Tg of N. The animals in turn may return a portion of the N to the system as manure. Animals, such as birds or insects also harvest some N and may return it to the system as excreta and corpse which are difficult to estimate. Organic manure is one of the important sources of N used in crop production. It is produced from crop, animal and human wastes and added ~0.17 Tg N to the soil during 1995-96. The wet N deposition (NO_3^- and NH_4^+) in agricultural soils in India during 1995-96 as estimated by Velmurugan et al. (2008) worked out to be ~0.81 Tg N. Nitrate N leaching beneath agricultural soils and through runoff was estimated to be ~0.06 Tg N. This agricultural leaching and run-off result in nitrate pollution of ground water bodies or N enrichment of river systems. Since irrigation is one of the essential components of modern agricultural production systems, ground water is utilized to irrigate ~36.25 m ha in India. As a result, 0.11 Tg N in the form of NO_3^- contained in the ground water is brought back into the agricultural production system.

Nitrogen use efficiency: Terms and calculations

Partial factor productivity *(kg product/kg N applied)*: crop yield per unit N applied.

Agronomic efficiency *(kg grain increase/kg N applied)*: crop yield increase per unit N applied.

Recovery efficiency *[(fertilized crop N uptake-unfertilized crop N uptake)/N applied]*: increase in N uptake by the crop per unit N added, usually for the first crop following application and usually expressed as a percent or fraction.

Removal efficiency *(crop N removal/N applied)*: N removed by the harvested portion of the crop per unit N applied, usually expressed as a percent or fraction.

Physiological efficiency *(kg grain increase/kg fertilizer N uptake)*: crop yield increase per unit fertilizer N taken up.

Improving nitrogen use efficiency in rice

A recent review of worldwide data on NUE for cereal crops from researcher-managed experimental plots reported that single-year fertilizer N recovery efficiencies averaged 65% for corn, 57% for wheat, and 46% for rice (Ladha et al., 2005). However, experimental plots do not accurately reflect the efficiencies obtainable on-farm. Differences in the scale of farming operations and management practices (i.e. tillage, seeding, weed and pest control, irrigation, harvesting) usually result in lower nutrient use efficiency. Nitrogen recovery in crops grown by farmers rarely exceeds 50% and is often much lower. A review of best available information suggests average N recovery efficiency for fields managed by farmers' ranges from about 20% to 30% under rainfed conditions and 30% to 40% under irrigated conditions. Cassman et al. (2002) and Shukla et al. (2004) looked at N fertilizer recovery under different situations (Table 1) and found N recovery averaged 31% for irrigated rice grown by Asian farmers and 40% for rice under field specific management. Fertilizer nutrients applied, but not taken up by the crop, are vulnerable to losses from leaching, erosion, and denitrification or volatilization in the case of N, or they could be temporarily immobilized in soil organic matter to be released at a later time, all of which impact apparent use efficiency.

Fertilizer use efficiency can be optimized by fertilizer best management practices that apply nutrients at the right rate, time, and place. The highest nutrient use efficiency always occurs at the lower parts of the yield response curve, where fertilizer inputs are lowest, but effectiveness of fertilizers in increasing crop yields and optimizing farmer profitability should not be sacrificed for the sake of efficiency alone. There must be a balance between optimal nutrient use efficiency and farmer profitability.

TABLE 1. *Nitrogen fertilizer recovery by rice from on-farm measurements*

Region	Number of farms	Average N levels kg N ha^{-1} (± SD)	REN % (± SD)
Asia-field specific management	179	117 ± 39	31 ± 18
Asia-field specific management (LCC)	179	112 ± 28	40 ± 18
Uttar Pradesh- farmers practice	75	138 ± 32	32 ± 11
Uttar Pradesh-LCC based	75	105 ± 15	49 ± 8

Source: Cassman et al. (2002); Shukla et al. (2004)

Strategies to enhance nitrogen use efficiency

Nitrogen management is the key for sustainable and profitable rice production in India. The fertilizer N use efficiency depends upon potential of cultivars, time, method, rate and source of N fertilization and rice ecologies. Traditional cultivars generally grown in water logged lowlands are low fertilizer responsive and are therefore raised either without fertilization (NPK) or with low doses of applied N, which is the major cause for low rice yield and optimal crop productivity. Many strategies have been developed to increase the efficiency of urea-N through proper timing, rate, placement, modified forms of fertilizer, and use of nitrification and urease inhibitors (Ladha et al., 2005; Shukla et al., 2004, 2006; Bijay Singh et al., 2008). The response to added nutrients varies markedly due to differences in weather, genotype, soil, agronomic practices, water regime, pest management, and crop history. Despite these differences, it is necessary to develop strategies to improve fertilizer-use efficiency.

Right rate

Rice is grown in different ecologies depending on cultivar, management practices, climate, etc. So it is critical that realistic yield goals are established and that nutrients are applied to meet the target yield. Over- or under-application will result in reduced nutrient use efficiency or losses in yield and crop quality. Soil testing remains one of the most powerful tools available for determining the nutrient supplying capacity of the soil, but to be useful for making appropriate fertilizer recommendations good calibration data is also necessary. Unfortunately, soil testing is not available in all regions of India because laboratories are using different methodology which are inaccessible or calibration data relevant to current cropping systems and yields are lacking. Other techniques, such as omission plots, are proving useful in determining the amount of fertilizer required for attaining a yield target. In this method, N, P, and K are applied at sufficiently high rates to ensure that yield is not limited by an insufficient supply of the added nutrients. Target yield can be determined from plots with unlimited NPK. One nutrient is omitted from the plots to determine a nutrient-limited yield. For example, an N omission plot receives no N, but sufficient P and K fertilizer to ensure that those nutrients are not limiting yield. The difference in grain yield between a fully fertilized plot and an N omission plot is the deficit between the crop demand for N and indigenous supply of N, which must be met by fertilizers. Nutrients removed in crops are also an important consideration. Unless nutrients removed in harvested grain and crop residues are replaced, soil fertility will be depleted.

Right time/ Site specific nitrogen management

The most efficient management practice to maximize plant uptake and minimize losses is to synchronize the N supply with the plant demand. This general concept of balancing supply and demand implies maintaining low levels of mineral N in soil when there is little or no plant growth, and providing sufficient N to meet plant requirements during periods of rapid growth (Peoples et al., 1995, Balasubramanian et al., 1998, 2004). Blanket fertilizer N recommendations, developed for large tracts having similar climate and land forms in rice based systems in India cannot help to increase NUE beyond a limit. Nitrogen use efficiency can be improved by adopting fertilizer, soil, water, and crop management practices that will maximize crop N uptake, minimize N losses, and optimize indigenous soil N supply. Further improvement can be achieved only by planning strategies for fertilizer N management responsive to temporal variations in crop N demand and field-to-field variability in soil-N supply. Improvement in the synchrony between crop N demand and the N supply from soil or the applied N fertilizer is likely to be the most promising strategy to improve NUE. Site-specific N management requires quantitative knowledge of crop nutrient need and expected indigenous nutrient supply and can be aimed at improving the recovery efficiency of applied fertilizer. The basic objective is to optimize the congruence of supply and demand of N (Giller et al., 2004). Depending on when and what decisions are made, site-specific N management (SSNM) can be (1) prescriptive, (2) corrective, or (3) a combination of both (Dobermann et al., 2004). In prescriptive N management, the amount and timing of N applications are prescribed before seeding based on N supply from indigenous sources, expected crop N demand, which is calculated from the target yield, expected efficiency of fertilizer N, and the expected risk from weather and pests. While prescriptive N management relies on information generated before the planting of a crop, corrective N management methods employ diagnostic tools to assess soil or crop N status during the growing season. Management decisions that increase fertilizer N use by crops can focus on two approaches: (1) increase fertilizer N use during the growing season when the fertilizer is applied and (2) decrease fertilizer N losses, thereby increasing the potential recovery of residual fertilizer N by the subsequent crops. Removing plant growth limiting factors would increase crop demand for N, leading to a greater use of available N and, consequently, higher NUE (Balasubramanian et al., 2004).

Poor fertilizer N use efficiency for rice production in India is an accepted fact. The agronomic N use efficiency (AEN) of the farmers' N-fertilizer practice is 5.2±3.4 kg kg^{-1} for the irrigated rice crop (Shukla et al., 2004, Bijay Singh et al., 2008, Pathak et al., 2006). A well-managed rice crop should have an AEN of 15–25 kg kg^{-1} under irrigated conditions if the N input is optimal. Nitrate leaching subject to excessive N input was one of the major causes for poor fertilizer N use efficiency in Indo-Gangetic plains of India while gaseous N losses is dominant cause in traditional rice growing areas. Furthermore, excessive N is applied mostly in the vegetative stage during the early growing season i.e., 56–85% of total N in the first 10 days after transplanting (Shukla et al., 2006). The improper timing of N application also contributed to the poor fertilizer N use efficiency for rice production.

The International Rice Research Institute (IRRI) developed site-specific N management (SSNM) such as real-time N management (RTNM) and fixed-time adjustable-dose N management (FTNM) to increase the fertilizer N use efficiency of irrigated rice. In RTNM, a certain rate of N fertilizer is applied only when leaf N content is below a critical level. Therefore, the timing and number of N applications and total N rates vary across seasons and locations. Leaf N content can be estimated non-destructively with a soil plant analysis development (SPAD) chlorophyll meter or leaf color chart (LCC) (Balasubramanian et al., 1998; Shukla et al., 2004). In FTNM, yield response to N application is estimated based on the difference between grain yield with a zero-N control and the target yield. The target yield is usually set at 85% of climatic yield potential. Total N rate is estimated based on the yield response and the target AEN. Total N is applied split at basal, mid-tillering, panicle initiation and heading. The rates of N topdressing at the key growth stages are adjusted according to leaf N status measured with SPAD or LCC. In this approach, the timing and number of N applications are fixed while the rate of each N application varies across seasons and locations.

Evaluation of RTNM in many Asian rice growing countries has generally shown that the same rice yield could be achieved with about 20–30% less N fertilizer applied, but increases in yield were rare (Peng et al., 1996; Balasubramanian et al., 1998; Singh et al., 2002). However, across eight sites in Asia, average grain yield increased by 11% and average N recovery efficiency (REN) increased from 31 to 40% by using FTNM compared with farmers' N fertilizer management (Dobermann et al., 2002). Experiment conducted at farmers field showed increase in recovery efficiency from 32±11 to 49±8 kg grain kg^{-1} N in sandy loam soils of Upper-Gangetic plains of India (Shukla et al., 2006). It has also been shown that both RTNM and FTNM could improve fertilizer N use efficiency of rice production in India (Ladha et al., 2005).

Chlorophyll meter

The SPAD - chlorophyll meter offers relative measurements of leaf chlorophyll content. Chlorophyll meters have their greatest sensitivity in the deficient to adequate range of N nutrition and have the advantage of being self-calibrating for different soils, seasons and cultivars. Although the chlorophyll meter enables users to quickly and easily measure leaf greenness, which is affected by leaf chlorophyll content, several other factors affect SPAD values. Differences in leaf thickness reflected in specific leaf weight are largely responsible for variations in the relationship between N content and SPAD values (Peng et al., 1993). Moreover, the linear relationship of SPAD values and N status in crops varies, depending on growth stages and cultivars. Finally, environmental and stress factors caused by excess or limited water, deficiency of nutrients other than N, and pests and diseases can also confound the SPAD readings.

Leaf color chart

The LCC, a plant health indicator, has been found to be an ideal tool to optimize the N supply in rice cropping, irrespective of the source of N applied, either inorganic or organic. The LCC is an easy to use, inexpensive and accurate tool for determining N status in rice plants. Conceptually, the LCC is based on the close link between leaf chlorophyll content and leaf N content over divergent growth stages. The LCC depicts gradients of green hues that are based on the wavelength characteristics of rice leaves, from yellowish-green to dark green. Farmers have always used their eyes as a subjective indicator of the rice crop's N status. With the LCC, they can make informed decisions regarding the need for fertilizer applications. Leaf color charts have been used extensively in Asia (Balasubramanian et al., 1998). The use of LCC, relatively an inexpensive tool, has shown great promise in optimizing N use in rice based on colour of the leaf which in turn reflects total N supply in different countries of Asia (Yadvinder-Singh et al., 2007). Farmers can easily use the LCC to quantitatively assess foliar N status and adjust top dressing accordingly as it is proved that the current recommendation of three split application at specified growth stages is not adequate to synchronize N supply with crop N demand (Bijay Singh et al., 2002; Shukla et al., 2004; Alam et al., 2005, 2006). By using LCC farmers saved 11-25 and 18-37 kg N ha^{-1} as compared to recommended dose and their own practice of N fertilization (Shukla et al., 2004) without a loss of rice yield.

Nitrogen management in rainfed lowland ecology

In rainfed lowland rice, split application of fertilizer N is often not practical due to adverse soil–water situations. Hence, the entire required amount of N has to be applied in one single application when the water regime is favorable. A single broadcast application, however, increases N loss. Deep placement of urea super granules (USG) has been proven to improve N fertilizer efficiency. Deep-point placement of urea fertilizer is probably the most effective application method in reducing nitrogen loss except in soils with high percolation rates (Katyal et al., 1985).The placement technology is best suited to conditions where the predominant N loss mechanism is ammonia volatilization rather than leaching or denitrification. Deep placement of USG thus has greater benefit over surface split application on soils with moderate to heavy texture, low permeability and percolation rate and high cation exchange capacity and pH. Environments and management factors conducive to high ammonia volatilization potential would benefit most from deep placement technology. Improved N recovery and efficiency of USG has been well documented for lowland rice, but its market availability and methods to achieve placement pose problems. The technology has very limited adoption because USG is not commercially available or manufactured in most countries and labor requirement is high with hand placement. Manual application creates more difficulties in handling the granules, besides taking 36-42 more hours per hectare, than 2 split broadcast applications of prilled urea. Applicators developed so far have not worked satisfactorily under standing water conditions and in direct seeded rice conditions due to hardness of the soil. Hence, it is necessary to develop a suitable applicator to overcome these difficulties. Alternatively, for direct seeded rice, N fertilizers can be subsoil-banded near seed rows. The placement technology, if adopted by the farmers of the potential lowland areas in eastern India, is expected to give an additional production of 5.6 m t of rice.

Placement technologies

Deep-point placement of USG at 5-10 cm depth (reduced soil layer) is one of the most efficient N management techniques developed for rice. It is, however, labor-intensive and hence, recent research has focused on the development and evaluation of less labor-intensive methods for deep placement, such as pneumatic injection of urea or USG, mechanical deep placement of urea solution, injection as a mud slurry and use of a USG dispenser (De Datta & Buresh, 1989).

Depending on temperature, thickness of polymer coating and moisture permeability co-situs placement of 'control-release urea-N fertilizers (CRUNF)' provides an innovative way to improve NUE and reduce labor. Co-situs placement brings the fertilizer closer to the emerging roots, thus inducing more N uptake, fertilizer recovery and increased efficiency. Better recovery and higher efficiency can also be achieved by matching N release from CRUNF with plant N demand.

Band placement of urea solution

Band placement of urea solution into the anaerobic soil layer has been as effective as deep placement of USG in reducing volatilization losses and improving grain yield (Buresh et al., 2008). The technology, however, has not been tested at farm-level due to its site-specificity, problems in maintaining the peristaltic pump to deliver N solution in subsoil at uniform rates, and greater labor demand than conventional urea application.

Deep-point placement of urea super granules

Agronomic, economic and environmental advantages of deep-point placement of USG have been well established along with the saving of 20-40% of the urea-N for the same grain yield, compared with conventional urea applications. Deep-point placement (5-10 cm depth) in anaerobic soil layer, (i) limits the concentration of N in floodwater and in the surface oxidized layer; (ii) decreases N losses through runoff, ammonia volatilization and denitrification; (iii) minimizes weed use of the applied fertilizer; (iv) minimizes NH_4^+ and P fixation and immobilization; (v) ensures prolonged N availability up to flowering; and (vi) stimulates biological N fixation (BNF) because floodwater concentration remains low.

In using USG, consideration of the following factors should help to ensure agronomic efficiency of deep-placed USG and increase the chances of obtaining additional yield:

1. *Soil factors:* Only use in soils having low water percolation rate and CEC of 10 meq 100 g^{-1} soil.
2. *Plant factors:* Give preference to short- to medium-duration dwarf rice varieties. For the long duration variety, basal deep-placed USG with a suitable topdressing of N as prilled urea at panicle initiation stage would be helpful.
3. *Management factors:* Apply basally 30 to 60 kg USG-N ha^{-1} using only USG of the right weight (1-2 g urea $granule^{-1}$). Place one super granule for each four hills at 7-10 cm soil depth using the right plant population and modified spacing. Use modified 20 × 15 cm or 20 × 20 cm spacing to facilitate efficient placement of USG by hand or machine. Workers should always use the so called traffic lane of the modified spacing for performing all post-transplanting field operations. When deep placement of USG is delayed after transplanting, extra care is necessary to close the holes left at the placement sites. When puddling is inadequate or improper and deep placement is done during transplanting, some care may be required to close the holes.

Slow release fertilizers

Appropriate modification in fertilizer source or management practices can lead to reduced losses of N and increased fertilizer N use efficiency. For example, slow-release N fertilizer developed by coating urea granules with sulphur has been tested *vis-a'-vis* ordinary urea in rice and this material out performed ordinary urea in almost all types of soils (Meelu et al., 1983; Bijay-Singh & Katyal, 1987). Oil derived from seeds of neem (*Azadirachta indica*) contains melicians (generally known as neem bitters) of which Epinimbin, Deacetyl, Salanin and Azadirachtin are the active fractions, which showed dose-dependent nitrification inhibition action (Devakumar & Goswami, 1992). Although it has been established that neem products when applied along with urea are capable of enhancing NUE in rice (Singh & Singh, 1986), large scale use of neem products along with urea could not become possible as process for large-scale coating of urea with neem products was not available. Also, large quantity of neem products required for coating and coated products were not available as per specifications laid down in the Indian Fertilizer Control Order. The form of added N plays a role in regulating N losses and influencing NUE. Nitrogen fertilizers predominantly contain N in the form of ammonia, nitrate or urea. Among these forms, nitrate is the most susceptible to leaching, ammonia the least and urea moderately susceptible. Ammonia and urea are more susceptible to volatilization loss of N than fertilizers containing nitrate. Controlled release compounds have the potential to improve NUE and many different forms are now available. Controlled release N fertilizers offer a good option to reduce N losses from the system because their delayed N release pattern may improve the match with crop demand.

Use of inhibitors

Fertilizer N use efficiency could be greatly increased if the hydrolysis of urea to ammonium by soil urease could be retarded by the use of urease inhibitors, or if nitrate accumulation during the cropping phase could be regulated by nitrification inhibitors.

Urease inhibitors

Several studies using PPD and NBPT as urease inhibitors have been conducted in flooded rice fields (Simpson et al., 1985, Buresh et al., 1988, Cai et al., 1989), but little reduction in NH_3 loss has been achieved by using these compounds as PPD is rapidly hydrolyses under the alkaline conditions or it decomposed due to the high temperatures reached in the floodwater (Chai & Bremner, 1987). Studies with another thiophosphorictriamide, thiophosphoryl triamide, showed that it too was a relatively weak inhibitor of urease activity. Appreciable inhibition was only achieved after it had been converted to its oxon analogue (McCarty & Bremner, 1989; Bremner et al., 1991). These studies indicate that the thiophosphorictriamides do not inhibit urease activity, but that the phosphorictriamides are potent inhibitors of urease activity.

Nitrification inhibitors

Since ammonia or ammonium-producing compounds are the main sources of fertilizer N, maintenance of the applied N in the ammonium form should mean that less N is lost by denitrification. One mechanism of maintaining added N as ammonium is to add a nitrification inhibitor with the fertilizer (Sahrawat et al., 1987). Numerous substances have been tested for their ability to inhibit nitrification, and several of these have been patented. Only a limited number of chemicals are available commercially for use in agriculture. These include 2-chloro-6 (trichloromethyl) pyridine (nitrapyrin), sulfathiazole, dicyandiamide, 2-amino-4-chloro-6-methyl pyrimidine, 2-mercapto-benzothiazole, thiourea and 5-ethoxy-3-trichloromethyl-1,2,4-thiadiazole (terrazole). Unfortunately, most of these compounds have limited usefulness (Keeney, 1983). For example, the most commonly used nitrification inhibitor, nitrapyrin, is seldom effective because of sorption on soil colloids, hydrolysis to 6-chloropicolinic acid and loss by volatilization. Positively charged ammonium N is retained by negatively charged soil colloids and is less subject to leaching and denitrification losses. One method of maintaining N in the soil as ammonium is to add a nitrification inhibitor with the fertilizer. Nitrification inhibitors, which slow the conversion of NH_4^+-N into NO_3^-- N, have been reported to increase NUE and crop yield (Prasad & Power, 1995). Application of these inhibitors could also have considerable influence on emissions of N_2O and methane from soil (Malla et al., 2005; Pathak & Nedwell, 2001). Most of nitrification inhibitors remain unpopular with farmers in South Asia because of their high cost and poor availability. Further research and development are needed to identify cheap locally available materials such as neem cake and neem oil, which can inhibit nitrification and increase NUE.

Conclusions

Since the agricultural N cycle cannot be separated from the global N cycle, hence for improving N use efficiency and to minimize N losses in rice based system, it is required a better understanding of the N cycle at regional level. There is always N flows between the agricultural system and the wider environment. The N supply through indigenous sources should be taken in to account properly for assessing the N need, inevitable losses and NUE for sustainable agricultural production. Nitrogen management should make possible to partly fill the gap between current relatively low NUE levels observed in farmers' fields and results achieved in well-managed research plots. Because more than half of world N consumption takes place in Asia, where farms are predominantly small-scale, the main challenge remains the transfer of improved practices to hundreds of millions of farmers. At the same time, financial support provided to governmental extension services is rapidly declining throughout the world. Partnerships involving governments, the industry and other stakeholders will be required to fill this gap. Considering that N is an essential part of our developmental paradigm, options to minimize N loss from agriculture to wider environment will have to be addressed at many different levels, such as establishing/updating national N information systems, improvements in fertilizer/biofertilizer formulations, enhancement of the N-use efficiency of our crops and farming systems/practices, reduced dependence on non-renewable energy sources, improvements in fossil-fuel quality, fuel-use efficiency and reduction of fossil-fuel use/abuse, reduction in NO*x* emissions from farming, industrial and vehicular sources, minimizing anthropogenic (including agri-industrial) reactive N load in naturally overloaded areas (e.g. geodeposits) and fragile ecosystems, better management of wetland ecosystems, etc.

References

Alam, M.M., Ladha, J.K., Khan, S.R., Foyjunnessa, Rashid, H., Khan, A.H., & Buresh, R.J. (2005). Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. *Agronomy Journal,* 97, 949-959.

Alam, M.M, Ladha, J.K., Khan, S.R., Foyjunnessa, Rashid, H., Khan, A.H., & Buresh, R.J. (2006). Nutrient management for increased productivity of rice-wheat cropping system in Bangladesh. *Field Crops Research,* 96, 374-386.

Balasubramanian, V., Alves, B., Aulakh, M.S., Bekunda, M., Cai, Z.C., Drinkwater, L., Mugendi, D., Van Kessel, C., & Oenema, O. (2004). Crop, environmental, and management factors affecting N use efficiency. In A.R. Mosier, J.K. Syers, J.R. Freney (Eds.), *Agriculture and the N cycle: Assessing the impacts of fertilizer use on food production and the environment.* (pp. 19-33). Paris, France : SCOPE 65.

Balasubramanian, V., Morales, A.C., Cruz, R.T., & Abdulrachman, S. (1998). On farm adaptation of knowledge intensive N management technologies for rice systems. *Nutrient Cycling in Agroecosystem,* 53, 59-69.

Bijay-Singh, Yadvinder-Singh, Ladha, J.K., Bronson, K.F., Balasubramanian, V., Jagdeep-Singh, Khind, C.S. (2002). Chlorophyll meter and leaf color chart based nitrogen management for rice and wheat in northern India. *Agronomy Journal,* 94, 821-829.

Bijay-Singh & Katyal, J.C. (1987). Relative efficacy of some new urea-based nitrogen fertilizers for growing wetland rice on a permeable alluvial soil. *Journal of Agricultural Science (Cambridge),* 109, 27-31.

Bijay-Singh, Shan, Y.H., Johnson-Beebout S.E., Yadvinder-Singh and Buresh, R.J. (2008). Crop residue management for lowland rice-based cropping systems in Asia. *Advances in Agronomy,* 98, 201-270.

Bremner, J.M., McCarty, G.W., & Higuchi, T. (1991). Persistence of the inhibitory effects of phosphoroamides on urea hydrolysis in soils. *Communications in Soil Science and Plant Analysis,* 22, 1519-1526.

Buresh, R.J., De Datta, S.K., Padilla, J.L., & Chua, T.T. (1988). Potential of inhibitors for increasing response of lowland rice to urea fertilization. *Agronomy Journal,* 80, 947-952.

Buresh R.J., Reddy K.R., & van Kessel, C. (2008). Nitrogen transformations in submerged soils. In J.S. Schepers, W.R. Raun (Eds.), *Nitrogen in agricultural systems.* Agronomy Monograph 49. (pp. 401-436). Madison, Wisconsin, USA: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.

Cai, G.X., Freney, J.R., Muirhead, W.A., Simpson, J.R., Chen, D.L., & Trevitt, A.C.F. (1989). The evaluation of urease inhibitors to improve the efficiency of urea as a N-source for flooded rice. *Soil Biology and Biochemistry,* 21, 137-145.

Cassman, K.G., Dobermann, A., & Walters, D. (2002). Agroecosystems, nitrogen use efficiency, and nitrogen management. *Ambio,* 31, 132-140.

Chai, H.S., & Bremner, J.M. (1987). Evaluation of some phosphoroamides as soil urease inhibitors. *Biology and Fertility of Soils,* 3, 189-194.

De Datta, S.K., & Buresh, R.J. (1989). Integrated nitrogen management in irrigated rice. *Advances in Soil Science,* 10, 143-169.

Devakumar, C., & Goswami, B.K. (1992). Nematicidal principles from neem isolated and bioassay of some melicians. *Pesticide Research Journal,* 4, 79-84.

Dobermann, A., Witt, C., & Dawe, D. (Eds.). (2004). *Increasing productivity of intensive rice systems through site-specific nutrient management.* (pp. 101-286). Enfield, N.H. and Los Banos, Philippines: Sci. Publ./ IRRI.

Dobermann, A., Witt, C., Dawe, D., Abdulrachman, S., Gines, H.C., Nagarajan, R., Satawathananont, S., Son, T.T., Tan, P.S., Wang, G.H., Chien, N.V., Thoa, V.T.K., Phung, C.V., Stalin, P., Muthukrishnan, P., Ravi, V., Babu, M., Chatuporn, S., Sookthongsa, J., Sun, Q., Fu, R., Simbahan, G.C., & Adviento, M.A.A. (2002). Site-specific nutrient management for intensive rice cropping systems in Asia. *Field Crops Research,* 74, 37-66.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z.C., Freney, J.R., Martinelli, L.A., Seitzinger, S.P., & Sutton, M.A. (2008). Transformation of the nitrogen cycle: Recent trends, questions, and potential solutions. *Science,* 320, 889–892.

Giller, K.E., Chalk, P.M., Dobermann, A., Hammond, L., Hever, P., Ladha, J.K., Maene, L., Nyamudeza, P., Sali, H., & Freney, J.R. (2004). Emerging technologies to increase the efficiency of use of fertilizer nitrogen. In A.R. Mosier, J.K. Syers, J.R. Freney (Eds.), *Agriculture and the N Cycle: Assessing the impacts of fertilizer use on food production and the environment.* (pp. 35-51). Paris, France : SCOPE 65.

Katyal, J.C., Bijay-Singh, Vlek, P.L.G., & Craswell, E.T. (1985). Fate and efficiency of nitrogen fertilizers applied to wetland rice in Punjab, India. *Fertilizer Research,* 6, 279-290.

Keeney, D.R. (1983). Factors affecting the persistence and bioactivity of nitrification inhibitors. In J.J. Meisinger, G.W. Randall, M.L. Vitosh (Eds.), *Nitrification Inhibitors- Potentials and limitations.* (pp. 33-46). Madison: American Society of Agronomy.

Ladha J.K., Pathak H., Krupnik T.J., Six J., & van Kessel, C. (2005). Efficiency of fertilizer nitrogen in cereal production: Retrospects and prospects. *Advances in Agronomy,* 87, 85-156.

Malla, G., Bhatia, A., Pathak, H., Prasad, S., Jain, N., & Singh, J. (2005). Mitigating nitrous oxide and methane emissions from soil under rice–wheat system with nitrification and urease inhibitors. *Chemosphere,* 58. 141-147.

McCarty, G.W., & Bremner, J.M. (1989). Formation of phosphoryl triamide by decomposition of thiophosphoryl triamide in soil. *Biology and Fertility of Soils,* 8, 290-292.

Meelu., O.P., Rekhi, R.S., Brar, J.S., & Katyal, J.C. (1983). Comparative efficiency of different modified urea materials in rice. In Proceedings of the Fertilizer Association of India Northern Region Seminar on Fertilizer Use Efficiency. (pp. 47-59). New Delhi: The Fertilizer Association of India.

Pathak, H., & Nedwell, D.B. (2001). Strategies to reduce nitrous oxide emission from soil with fertilizer selection and nitrification inhibitor. *Water Air and Soil Pollution,* 129, 217-228.

Pathak H., Li, C., Wassmann, R., & Ladha, J.K. (2006). Simulation of nitrogen balance in the rice-wheat systems of the Indo- Gangetic plains. *Soil Science Society of America Journal,* 70, 1612-1622.

Peng, S., Garcia, F.V., Laza, R.C., & Cassman, K.G. (1993). Adjustment for specific leaf weight improves chlorophyll meter's estimate of rice leaf nitrogen concentration. *Agronomy Journal*, 85, 987-990.

Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Visperas, R.M., & Cassman, K.G. (1996). Increased N-use efficiency using a chlorophyll meter on high yielding irrigated rice. *Field Crops Research*, 47, 243–252.

Peoples, M.B., Freney, J.R., & Mosier, A.R. (1995). Minimizing gaseous losses of nitrogen. In P.E. Bacon (Ed.), *Nitrogen fertilization in the environment*. (pp. 565-602). New York: Marcel Dekker.

Prasad, R., & Power, J.F. (1995). Nitrification inhibitors for agriculture, health and the environment. *Advances in Agronomy*, 54, 233-281.

Sahrawat, K.L., Keeney, D.R., & Adams, S.S. (1987). Ability of nitrapyrin, dicyandiamide and acetylene to retard nitrification in a mineral and an organic soil. *Plant and Soil*, 101, 179-182.

Shukla, A.K., Singh V.K., Dwivedi B.S., Sharma S.K., & Singh, Y. (2006). Nitrogen use efficiencies using leaf colour chart in rice (*Oryza sativa*) and wheat (T*riticum aestivam*) cropping system. *Indian Journal of Agricultural Sciences*, 76, 651-656.

Shukla, A.K., Ladha, J.K., Singh, V.K., Dwivedi, B.S., Blasubramanian, V., Gupta, R.K., Sharma, S.K., Singh, Y., Pathak, H., Pandey, P.S., Padre, A.T., & Yadav, R.L. (2004). Calibrating the leaf color chart for nitrogen management in different genotypes of rice and wheat in a system perspective. *Agronomy Journal*, 96, 1606-1621.

Simpson, J.R., Freney, J.R., Wetselaar, R., Muirhead, W.A., Leuning, R., & Denmead, O.T. (1985). Transformations and losses of urea nitrogen after application to flooded rice. *Australian Journal of Agricultural Research*, 35, 189-200.

Singh, M., & Singh, T.A. (1986). Leaching losses of nitrogen from urea as affected by application of neem-cake. *Journal of the Indian Society of Soil Science*, 34, 766-773.

Singh, B., Singh, Y., Ladha, J.K. et al. (2002). Chlorophyll meter- and leaf color chart-based nitrogen management for rice and wheat in northwestern India. *Agronomy Journal*, 94, 821-829.

Spiertz, J.H.J. (2010). Nitrogen, sustainable agriculture and food security: A review. *Agronomy for Sustainable Development*, 30, 43-55.

Velmurugan A., Dadhwal V.K., & Abrol Y.P. (2008). Regional nitrogen cycle: An Indian perspective. *Current Science*, 94, 1455-1468.

Yadvinder Singh, Singh, B., Ladha, J.K., Bains, J.S., Gupta, R.K., Singh, J., & Balasubramanian, V. (2007). On-farm evaluation of leaf color chart for need-based nitrogen management in irrigated transplanted rice in northwestern India. *Nutrient Cycling in Agroecosystem*, 78, 167-176.

*****

Chapter 13

Climate resilient rice cultivars adapted to excess water

R.K. Sarkar
Central Rice Research Institute, Cuttack, Odisha, India
e-mail: rksarkarcrri@gmail.com

The resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (e.g. flooding, drought) and other global change drivers like land use change and over exploitation of resources (IPCC, 2007). By 2030, the average temperatures in India will rise by 1.7-2.2°C and extreme temperatures by 1-4°C in comparison to the 1970s. The hotter summers and warmer winters will lead to substantial changes in agricultural production, water flows, and could cause dramatic changes in the country's weather; as reported by the Indian Network for Climate Change Assessment (INCCA, 2010). Rising temperatures will accelerate the rate of melting of snow and glacier ice, increasing seasonal peak flows of the Himalayan headwaters. This in turn may lead to an increased frequency of flooding particularly along the rivers whose channel capacity has been reduced by sedimentation (Aggarwal et al., 2004).

Coasts are projected to be exposed to increasing risks, including coastal erosion, due to climate change and sea level rise and many millions more people than today are projected to experience floods every year due to sea level rise (IPCC, 2007). Excessive flooding poses risks to human life and is a major contributor to the poverty and vulnerability of marginalized communities. It is estimated that the flood-affected area has more than doubled in size from about 5% (19 m ha) to about 12% (40 m ha) of India's geographic area in the past five decades. Adding to these already high risks, the climate projections suggest that temperatures, precipitation and flooding are likely to increase, with adverse impacts on crop yields and farm incomes. Among the more substantial effects is a spatial shift in the pattern of rainfall towards the already flood-prone coastal areas. As an example of the implied magnitudes, the probability that the discharge might exceed 25,000 cubic meters per second (at the measuring station at Naraj on the Mahanadi River in Odisha), is currently low-about 2%. But under climate change, this is projected to rise dramatically to over 10% (World Bank Report, 2008). Productive deltaic agricultural land would become more vulnerable to floods, to the impacts of possibly more severe tropical cyclones and to rising sea levels. A possible sea-level rise of 15 to 38 cm by the 2050s (Douglas, 2009) would cause saline water to penetrate further inland and ultimately displace some 35 million people around the Bay of Bengal, and change the conditions in other deltas and coastal plains on a similar scale (Wassmann et al., 2009). Climate changes appear to be influencing the monsoon and tropical cyclones, the two prime drivers of flood events in South Asia (Unnikrishnan et al., 2006). Average annual precipitation of Odisha is around 1500 mm and 75 % of it is received through South-west monsoon during June to September (Fig. 1). If we look at the rainfall pattern of the last decade, we find that there is a huge deviation from the normal, and 300-400 mm rainfall is received within a span of 1-2 days, causing severe flood and drought in subsequent days (Singh et al., 2011). The rainfall has become irregular and unpredictable. Therefore, a number of interacting problems threaten future and present sustainability and food security.

In developing countries especially, in Asia, food security means the availability of the principal staple food rice. Worldwide, rice provides 27% of the dietary energy supply, and 20% of the

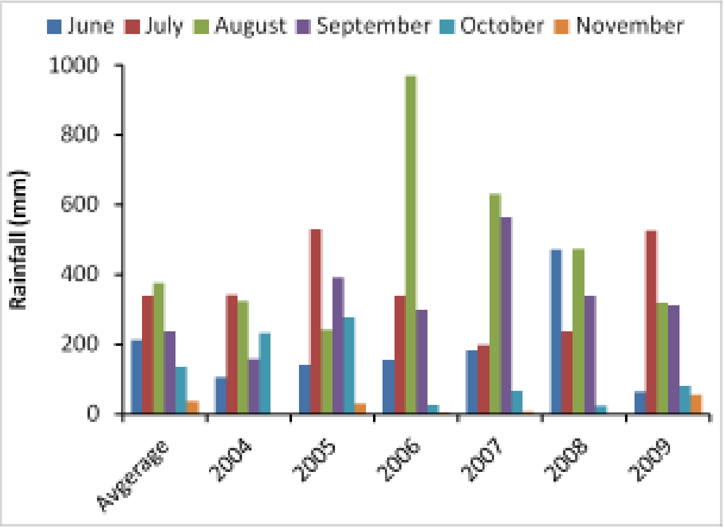


FIGURE 1. *Variability in rainfall during the main rice growing season of Odisha*

dietary protein intake. In Asia alone, more than 2 billion people obtain 60–70 % of their energy intake from rice and its derived products. Rice is currently the most rapidly growing food source in Africa (FAO, 2004). Adaptation to the adverse impacts of climate change has been recognized as a priority area for national and international policy. The findings of the Fourth Assessment Report of the IPCC have reemphasized the urgency of action and the scale of response needed to cope with climate change outcomes. The scientific community has an important role to play in advancing the information and knowledge base that would help in identifying, developing and implementing effective responses to enhance adaptive capacity and reduce vulnerability. Geographically rice is being grown in lands as far as 50°N latitude (Aiwei, China) to 30°S latitude (New South Wales, Australia). It is grown in lands situated below sea level in Kerela to 2761 m above sea level (Jumulla valley, Nepal) thus making its presence in all the environments and all continents of World (Chang, 2000). In India the area under rice cultivation is 43.7 m ha with an annual production of 91.1 m t and an average productivity of 2.09 t ha^{-1} (2006-07) (Anonymous, 2007). In India rice is grown in various ecologies ranging from irrigated to uplands, rainfed lowland, deep water and tidal wetlands. So rice is a versatile crop and it can be grown in different land situations. It is further emphasized that rice is a hope to encounter the adverse effect of climate change to secure food and livelihood.

Production constraints in changing climate due to excess water

Rice areas encompass a great diversity of growing conditions that vary based on the amount and duration of rainfall, depth and extent of standing water, flooding frequency, time of flooding within the growing season, soil type and topography. Besides biological constraint, the physical constraint influences the rice productivity which is more paramount in a changing climate. Crucial for survival and yield of the rice crop are the age of plants at the start of inundation, the rate of water rise, and the duration of the floods. Many parts of the tidal, deepwater and rainfed lowland rice areas are faced with abrupt increases in water level that completely inundate the crop, commonly called flash floods. These floods occur after local or remote heavy rains and may completely submerge the crop for several days with the consequent delays in development and reduced stand.

India has almost all the ecology of flood prone rice ranging from flash floods to semi-deep and deepwater, where submergence occurs during early or late vegetative stages for about one to two weeks (in flash floods) and 3-6 weeks in semi-deep conditions (Sarkar et al., 2009a). Stagnant flooding also occurs in several parts of Bihar, Odisha, West Bengal and Assam, inundating rice crops to different depths and durations and adversely affecting the growth and yield. In flash flood areas, the water is invariably laden with silt which is deposited on leaf surfaces causing mechanical damage and diminishes underwater photosynthesis by rice plants. In deep water areas where dry direct seeding is practiced in the month of May and June, crop suffers from drought if rain is delayed after initial showers, while submergence occurs at early growth stages due to heavy rains in the month of July. In flash flood areas too, submergence and or drought could occur either alone or in combination depending upon the timing and intensity of rains causing yield penalty in both lowland and irrigated rice. Impacts are very likely to increase due to increased frequencies and intensities of some extreme weather events.

Cultivation strategies to overcome excess water effects

Flooding may occur any time during the crop growing period, results accumulation of water on field. Through genetic enhancement and proper management practices, the tolerance of plant to excess water situation can be enhanced.

Cultivar with greater plasticity for rainfed lowland- Photoperiod sensitivity

Traditional varieties adapted to the lowland and deepwater ecosystems are generally not high yielding types, but photo-sensitive in nature. Due to the photo-sensitivity these cultivars avoid the submergence stress at the time of flowering. The possession of photo-sensitivity is significant because complete submergence during flowering even for a few days affects grain formation and spikelets become completely sterile. Besides, photoperiod-sensitive cultivars possess high plasticity and can be planted at different ages without much loss in grain yield (Reddy et al., 2009). The farmers of eastern India sometimes plant more than two months old seedlings to avoid complete inundation especially in deepwater and water stagnant areas. *Bolan* or double transplanting is a traditional practice of farmers in submergence prone areas in North-eastern part of West Bengal, India. Use of photoperiod-sensitive cultivars has helped in adopting this technology.

Anaerobic seeding tolerance

Direct seeding under the surface of flooded soil is known as anaerobic seeding, which requires less labour, and less energy than transplanting. Anaerobic seeding not only reduces the cost of cultivation but is also environment friendly due to reduction in the application of herbicide compared to the other method of direct sowing. In rainfed lowland, direct dry seeding is the common practice. If flood and or heavy rainfall occurs, due to low lying topographical condition of rainfed lowland, water stagnates, establishment of rice may not be proper and sometimes total area becomes barren. If rice varieties which can germinate and grow under flooded soil surface are available, the constraints of both direct wet and dry sowing would be solved.

Screening technique for anaerobic germination

Small tray (minimum height of the tray is 12 cm) is filled up with fine clay-loam farm soil. Dry seeds are sown just below soil surface. Immediately after sowing, the tray is filled up with 10 cm depth of standing water, which is kept in ambient environmental conditions under the temperature range of 25-32°C. Crop establishment or survival are counted after 15 days of sowing. Emergence of leaf tips above the water surface is considered as establishment or survival. Germination under non-stressed condition is taken as 100 % and accordingly the survival % is calculated for each cultivar under stressed condition. Some rice genotypes that are tolerant to anaerobic seeding are AC917, AC1160, AC1571, AC1631, AC39416, AC40413, AC40561, AC40598, AC41625, AC41644 and EC516602.

Seed invigoration to improve under water plant establishment

Soak the seeds with simple tap water or 2% Jamun (*Syzygium cumini)* leaves extract for 14-16 hoursand dry the seeds under the sun till the moisture percentage of seeds come down to 10-12%. This process of treatment to rice seeds is called “Priming”. The primed seed can be stored up to three months without any germination deterioration (Table 1).

TABLE 1. *Effect of seed priming on yield and yield attributes in two rice cultivars under non-stressed and stressed conditions (anaerobic germination)*

Yield and its attributes	Swarna			Swarna *Sub1*			LSD
	CNP	PNW	PLE	CNP	PNW	PLE	($p<0.05$)
A. Non-stressed conditions							
Panicle number (m^{-2})	295	339	344	292	342	349	28
Single panicle weight (g)	2.46	2.52	2.78	2.23	2.49	2.78	0.23
Fertile spikelet (%)	73.0	72.5	71.5	66.7	72.2	71.5	4.2
Harvest Index	0.44	0.41	0.44	0.38	0.41	0.41	0.04
Grain yield (t ha^{-1})	5.31	5.68	5.68	4.84	5.35	5.08	0.41
B. Under anaerobic germination							
Panicle number (m^{-2})	166	218	257	208	295	275	28
Single panicle weight (g)	2.28	3.11	2.93	2.41	2.68	3.16	0.23
Fertile spikelet (%)	64.1	68.4	74.2	65.9	71.9	69.7	4.2
Harvest Index	0.39	0.41	0.42	0.39	0.40	0.44	0.04
Grain yield (t ha^{-1})	3.52	3.98	4.02	3.28	5.22	4.89	0.41

CNP: Controlled no priming; PNW: Priming with normal tap water; PLE: Priming with 2% leaf extracts of *Syzygium cumini*

Offset the adverse effects of complete submergence

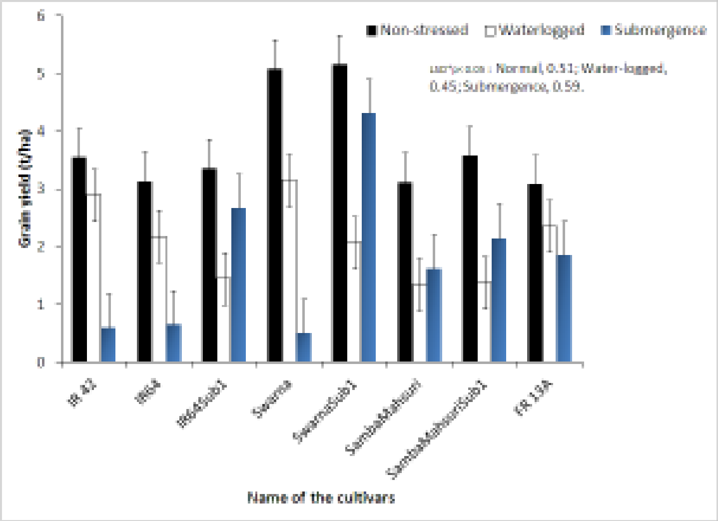


FIGURE. 2. *Performance of rice cultivars with and without Sub1 at different water regimes*

Submergence tolerant cultivars

Rice genotypes with *Sub1* have great potential for improving the productivity of rainfed lowland or areas prone to flash-flooding (Sarkar et al., 2009b). Introgression of *Sub1* has been made to many popular rice varieties including Swarna. Under flash-flooding, genotypes with *Sub1* survived complete submergence stress with turbid water for up to 12 days, whereas genotypes without *Sub1* did not survive (Fig. 2). It has been observed that even under mild excess water stress (submergence period 5-6 days) in natural farmers' fields conditions, Swarna*Sub1* produced higher grain yield than Swarna at all sites with a yield advantage of up to 1.65 t ha^{-1} (an average of 0.81 t ha^{-1} over five sites).

Nutrient status

Nutrient status of seedling before submergence affects the survival of rice during submergence. Therefore, besides genetic improvement, manipulation of some of the traits associated with submergence tolerance through certain management practices, could substantially enhance survival and productivity of rice in flood prone area, particularly when both are combined (Das et al., 2009; Sarkar & Panda, 2009; Das et al., 2005; Das et al., 2001; Sarkar, 1998). Survival of both FR13A (with *Sub1*) and IR42 decreased substantially in seedlings with high nitrogen dose. The fact that there is a negative relationship between nitrogen and starch content and therefore, a low nitrogen level in a plant contributed to an accumulation of starch in the shoot (Sarkar, 1998). It was observed that application of N: P: K @ 15:40:20 kg ha^{-1} at the seed bed helped in the formation of robust seedlings which could withstand complete submergence stress to a greater extent. A significant positive correlation was also noticed between application of phosphorous and submergence tolerance. Apart from better survival, plants receiving phosphorous showed greater accumulation of carbohydrate before submergence and had less elongation during submergence compared to the plants without additional phosphorous application. Robust seedlings can be produced through nursery management by sowing good quality seeds @ 30 g m^{-2} and application of N, P, and K @ 15, 40 and 20 kg ha^{-1} on seed bed. For raising robust seedlings under field conditions, the seed rate would be 60-70 kg ha^{-1} and the doses of N: P: K would be 15: 60: 40 kg ha^{-1}, respectively. Later on nitrogen management is to be done depending on the stagnation of water on rice field. Nitrogen application up to meiosis stage (15 days before flowering) improves grain yield production; therefore depending upon the water regime nitrogen should be applied @ 40 kg N ha^{-1} in two split doses.

Adaptation strategies under stagnant water flooding

Rice plants that exhibit only limited elongation during submergence often show tolerance to complete flooding. The ideal response to stagnant water flooding is submergence tolerance (survival under water) together with some elongating ability. This ideotype is suitable when water level increases and then (i) stays at that level, (ii) recedes only partly or (iii) recedes but then rises again and stays for longer duration. "KHODA" as submergence tolerant line possesses submergence tolerant gene '*Sub1*', has limited elongation capacity with greater regeneration ability is better than Swarna*Sub1* and is suitable for highly fluctuating water level.

Avoiding common pitfalls in submergence screening

The quality of floodwater influences the survival of plants, hence for screening the cultivars, greater attention should be given to the susceptible ones. Depending on the quality of floodwater, duration could be decided so that mortality of the susceptible check is nearer to 100%. Extreme yellowing of leaves and softening of base is a harbinger of plant death and on that basis a decision about the total days of submergence can also be taken. Under clear water submergence, stress can be applied for 10-15 days depending upon the state of susceptible check.

Flash flood

A. Under field tanks

The mechanisms of survival under flash flooding and stagnant water conditions are different. Plants are raised under direct seeded condition. Generally, 18-21 days old seedlings are completely submerged under 70-80 cm of water. Plant height is taken before and after submergence to know the elongation ability which may give an idea about the suitability of plants for flash flood or stagnant water conditions. Care should be taken so that no leaf tips come above the water surface. Finally number of

FIGURE 3 (A & B). *Screening of submergence tolerance of rice in tank*

survivors is counted after 10 days of de-submergence (Fig. 3A & 3B). Survival (%) = (Number of plants after 10 days of de-submergence/number of plants before submergence) x 100.

B. Under net house conditions

Seeds are direct seeded in small trays. After 10 days of sowing, the trays along with seedlings are submerged in small concrete tanks under 80 cm depth of water for 10 days. Plant survival count is taken after 10 days of drainage of water. Plant height is taken immediately after drainage (Fig. 4). This technique is highly useful for transgenic plant as well as for other genetical studies. This saves time and needs limited resources and can be used to distinguish between tolerant and susceptible types. Some rice genotypes that are tolerant to complete submergence are Swarna*Sub1*, IR64*Sub1*, Savitri*Sub1*, Khoda, Kalaputia, Atiranga, Gangasiuli, Kusuma, AC42088, AC38575, AC37887 and AC39968.

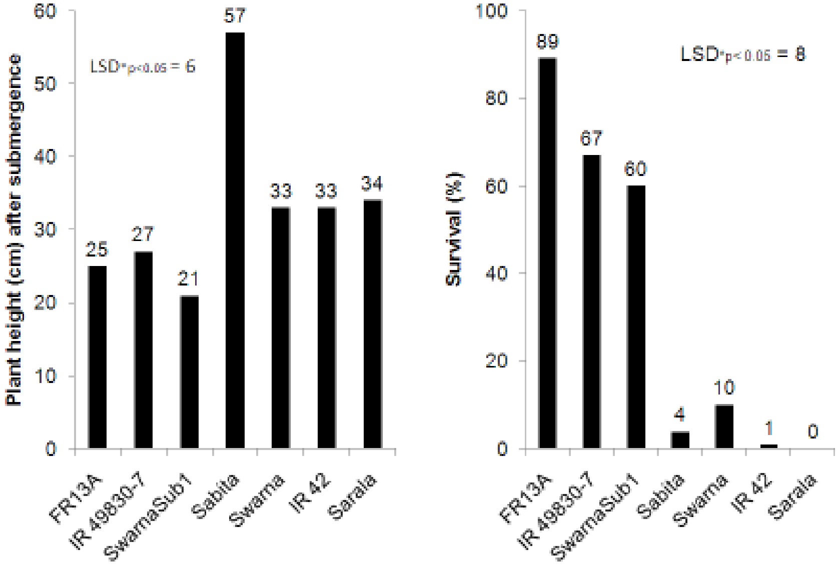


FIGURE 4. *Survival percentage and changes in plant height after 10 days of submergence under net-house tray sown condition*

Screening for stagnant water flooding

Screening plants for semi-deep to deep water conditions is some what different, where elongation ability is also an important parameter. However, extensive elongation which occurs in floating rice is not desirable for deep water conditions (up to a water depth of 100 cm). Plants with straight, erect leaves that come up above the water are suitable for the condition, but the cultivars would be termed as best where elongation stop once the leaves emerge out of water.

Plants are raised under direct seeded condition with basal fertilizers (N: P: K @ 20: 30: 30 kg ha^{-1}). Thirty to thirty-five-days old seedlings are submerged under 70-80 cm of water depth. The depth of water is maintained at least for one month. Plant height and survival percentage are taken before and after one month of inundation. Some rice genotypes that are tolerant to stagnant water flooding are Atiranga, Gangasiuli, Kusuma, Khoda, AC39416, AC42084, AC42102, AC42220, AC42243, AC42254, and AC42271.

Conclusions

The most cost effective ways to help the poor farmers is to breed climate resilient cultivars, which can adapt the changes, can save resources and drudgery to some extent. Of course it is a daunting task because of uncertainty about the magnitude of possible climate changes, their geographic distribution, and the long lead times needed to implement adaptation efforts. Rice crop with multiple abiotic stress tolerance are needed. The present knowledge though inadequate, can serve an incredible role in mitigating the excess water stress.

References

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

Anonymous. (2007). *Agricultural statistics at a glance*, 2007. Directorate of Economics and Statistics, Ministry of Agriculture, Govt. of India.

Chang, Te-Tzu. (2000). Rice. In K.F. Kiple, K.C. Ornelas (Eds.), *The Cambridge world history of food*. Chapter II (A. 7). UK: Cambridge university Press.

Das, K.K., Panda, D., Sarkar, R.K., Reddy, J.N., & Ismail, A.M. (2009). Submergence tolerance in relation to variable floodwater conditions in rice. *Environmental and Experimental Botany*, 66, 425-434.

Das, K.K., Sarkar, R.K., & Ismail, A.M. (2005). Elongation ability and non-structural carbohydrate levels in relation to submergence tolerance in rice. *Plant Science*, 168, 131-136.

Das, K.K., & Sarkar, R.K. (2001). Post flood changes on the status of chlorophyll, carbohydrate and nitrogen content and its association with submergence tolerance in rice. *Plant Achieves*, 1, 15-19.

Douglas, I. (2009). Climate change, flooding and food security in South Asia. *Food Security*, 1, 127-136.

Food and Agriculture Organization Statistics (FAOSTAT). (2004). Statistical Databases. Italy: Food and Agricultural Organization of the United Nations.

INCCA (Indian Network for Climate Change Assessment). (2010). Climate change and India: A 4x4 assessment, A sartorial and regional analysis for 2030s: Ministry of Environment and Forests, Government of India.

Intergovernmental Panel on Climate Change (IPCC). (2007). *Climate change - The scientific basis*. Cambridge Univ., UK: Cambridge Press.

Reddy, J.N., Sarkar, R.K., Patnaik, S.S.C., Singh, D.P., Singh, U.S., Ismail, A.M., & Mackill, D.J. (2009). Improvement of rice germplasm for rainfed lowland of eastern India. *SABRAO Journal of Breeding and Genetics*, 41, Special Supplement, August 2009. ISSN 102907073.

Sarkar, R.K. (1998). Saccharide content and growth parameters in relation with flooding tolerance in rice. *Biologia Plantarum*, 40, 597-603.

Sarkar, R.K., & Panda, D. (2009). Distinction and characterisation of submergence tolerant and sensitive rice cultivars, probed by the fluorescence OJIP rise kinetics. *Functional Plant Physiology*, 36, 1-12.

Sarkar, R.K., Reddy, J.N., Das, K.K., Ram, P.C., Singh, P.N., Mazid, M.A., Sommut, W., Pane, H., Sharma, S.G., & Ismail, A.M. (2009a). Biophysical constraints in flood-prone ecosystems: Impacts and prospects for enhancing and sustaining productivity. In S.M. Haefele, A.M. Ismail (Eds.), *Natural resource management for poverty reduction and environmental sustainability in fragile rice-based systems*. Limited Proceedings No. 15. (pp. 67-81). Los Banos, Philippines: International Rice Research Institute.

Sarkar, R.K., Panda, D., Reddy, J.N., Patnaik, S.S.C., Mackil, D.J., & Ismail, A.M. (2009b). Performance of submergence tolerant rice (*Oryza sativa*) genotypes carrying the Sub1 quantitative trait locus under stressed and non-stressed natural field conditions. *Indian Journal of Agricultural Sciences*, 79, 876-883.

Singh, D.P., Mahata, K.R., & Ismail, A.M. (2011). Increasing rice productivity in coastal saline areas of the Mahanadi delta, India through salt tolerant varieties and improved crop management. In *Deltas under climate change: The challenges of adaptation*. International Conference Delta 2011, 2nd - 4th March, Hanoi, Vietnam.

Unnikrishnan, A.S., Rupa Kumar, K., Fernandes, S.E., Michael, G.S., & Patwardhan, S.K. (2006). Sea level changes along the Indian coast: Observations and projections. *Current Science,* 90, 362-363.

Wassmann, R., Jagadish, S.V.K., Heuer, S., Ismail, A.M., Redona, E., Serraj, R., Singh, R.K., Howell, G., Pathak, H., & Sumfleth, K. (2009). Climate change affecting rice production: The physiological and agronomic basis for possible adaptation strategies. *Advances in Agronomy,* 101, 60-122.

World Bank (2008). Climate change impacts in drought and flood affected areas: Case studies in India. *Report No. 43946-IN*, 1-162.

*****

Chapter 14

C_4 Rice: Meeting food security in the era of climate change

M.J. Baig* **and Padmini Swain**
Central Rice Research Institute, Cuttack, Odisha, India
*e-mail: mjbaigcrri@gmail.com

Agriculture is the indispensable base of human society and the nature and productivity of agriculture are determined by water and climate. Today, the world's population is 7.02 billion, and 5.1 billion live in the developing world where most of the world's existing poverty is concentrated. Over the next 50 years, the world population will increase by about 50% and climate change will probably result in more extreme variations in weather and cause adverse shifts in the world's existing climate patterns.

Each hectare of land used for rice production in Asia currently provides food for 27 people, but by 2050 that land will have to support at least 43 people. Feeding the 5.6 billion Asians in the 21st century will require a second Green Revolution to boost yields by 50% using less water and fertilizer. Theoretical models have been used to examine this problem and they suggest that this can be done only by increasing the efficiency with which photosynthesis uses solar energy. Fortunately, evolution has provided an example of a much more efficient photosynthetic system (C_4) than that possessed by rice or wheat (C_3). Maize and sugarcane are some examples of C_4 plants.

Solar energy captured in photosynthesis over the duration of a crop gives it capacity to grow. The upper limit to crop biomass is determined by the laws of thermodynamics and mass conservation. At the limit, the total biomass is simply a function of the total quantity of solar energy captured and the efficiency with which that energy is made available for synthetic processes. Total solar energy absorption is largely a function of canopy architecture and crop duration. The efficiency of energy use is largely determined by photorespiration, dark respiration and losses of biomass that occur owing to senescence. The opportunities for reducing dark respiration are very limited and senescence is essential in terms of recycling essential nutrients from the vegetative portions of the crop to the reproductive ones. There are many evolutionary examples of plants that have eliminated photorespiration by concentrating carbon dioxide (CO_2) around the photosynthetic enzyme rubisco using a four carbon acid (C_4) cycle. Plants such as rice that do not have a concentrating CO_2 mechanism, fix CO_2 into three carbon acids (C_3 plants); their photosynthetic rates in hot environments are about half that of C_4 plants. C_4 plants have double the water use efficiency of C_3 plants, and use about 40% less nitrogen to achieve 50% higher yields.

The repeated evolution of C_4 photosynthesis indicates that it should be feasible to create C_4 rice plants by engineering C_4 genes into C_3 rice and replicating strong selection pressure for C_4 traits that we think exist in nature. The development of the C_4 system can be seen as an addition to the C_3 system and it is now clear that the C_3 and C_4 syndromes are not as rigidly separated as was first thought. The enzymes that are prominent in the C_4 pathway also exist in C_3 leaves although with very low activity. More surprisingly, there is a well-developed C_4 pathway in certain locations in C_3 plants: in the green tissue around vascular bundles, and probably in rice spikelet. On the other hand maize, a thoroughly C_4 plant, has patches of C_3 tissue wherever a mesophyll cell is not adjacent to a bundle sheath cell particularly in leaf sheaths and husk leaves. Some of the wild relatives of rice have C_4 like anatomical features and others may have CO_2 compensation points usually associated with C_3-C_4 intermediates.

Photosynthesis and its classification

Photosynthesis is the process by which plants, some bacteria, and some protistans use the energy from sunlight to produce sugar, which cellular respiration converts into ATP, the “fuel” used by all living things. The conversion of unusable sunlight energy into usable chemical energy is associated with the actions of the green pigment chlorophyll. Most of the time, the photosynthetic process uses water and releases the oxygen that we absolutely must have to stay alive. The overall reaction of this process as (Eq. 1).

$$6H_2O + 6CO_2 \longrightarrow C_6H_{12}O_6 + 6O_2 \text{ .... } (1)$$

C_3 and C_4 plants

The difference occurs in the second part of photosynthesis, the Calvin-Benson cycle, which “fixes” CO_2 into carbohydrates. The Calvin-Benson cycle (in “normal”, C_3 plants) consists of three processes: 1. The fixation of CO_2 in to a 5-carbon “receptor” (ribulose 1,5-bisphosphate, better known as RuBP), which results in two 3-carbon molecules (a sugar-phospate called 3-phosphoglycerate, or 3PG), a reaction catalyzed by the protein rubisco, 2. The reduction of 3PG to form a carbohydrate, glyceraldehyde 3-phosphate (G3P) and 3. Regeneration of the original receptor, RuBP.

Every “turn” of this cycle, one CO_2 is fixed. The problem comes in the first part of the cycle, where rubisco is used. Rubisco can either grab onto CO_2 or O_2. If it latches onto CO_2 as it should, then the first part of the cycle produces 2x 3PG, as it should. If it latches onto O_2 instead, then the first part of the cycle produces one 3PG, and one glycolate. Now, C_3 plants have evolved ways to reclaim at least some of the carbons channeled away as glycolate, by feeding glycolate through a peroxisome and a mitochondrion, where it undergoes several transformations and some of it is released back out as CO_2 (this is the pathway called photorespiration). However, it reduces the net carbon fixation by about 25%. C_3 plants, accounting for more than 95% of earth’s plant species, use rubisco to make a three-carbon compound as the first stable product of carbon fixation. C_3 plants flourish in cool, wet, and cloudy climates, where light levels may be low, because the metabolic pathway is more energy efficient, and if water is plentiful, the stomata can stay open and let in more CO_2. However, carbon losses through photorespiration are high.

Rubisco has about 10x more affinity for CO_2 than it does for O_2, so under normal circumstances this is not a problem. However, on very hot, dry days plants close the stomata in their leaves in order to minimize the loss of water and this interferes with gas exchange as well. As CO_2 is used up by the normal Calvin-Benson cycle, the balance of CO_2:O_2 inside the leaf alters in favor of O_2, and rubsico starts to grab it instead. This both slows down photosynthesis and reduces its carbon fixation overall. The C_4 plants have introduced an extra bit into the Calvin-Benson cycle, an extra early reaction that fixes CO_2 into not 3-carbon sugars, but 4-carbon sugars called oxaloacetate (hence the names, by the way, C_3 for 3-carbon and C_4 for 4-carbon sugars) by plunking CO_2 onto a different receptor molecule (phosphoenolpyruvate, or PEP) by way of the enzyme PEP carboxylase. PEP carboxylase has two advantages over rubisco: it has no affinity for O_2 at all, and it finds and fixes CO_2 even at very low CO_2 levels. And oxaloacetate has an advantage over 3PG, in low-CO_2 circumstances some of it degrades to form CO_2 again in the mesophyll, the cells which carry CO_2 to rubisco. As a result, the C_4 plants can close their stomata to retain moisture under hot, dry conditions, but still keep photosynthesis ticking over at good efficiency. C_4 plants possess biochemical and anatomical mechanisms to raise the intercellular CO_2 concentration at the site of fixation, and this reduces, and sometimes eliminates, carbon losses by photorespiration. C_4

plants, which inhabit hot, dry environments, have very high water-use efficiency, so that there can be up to twice as much photosynthesis per gram of water as in C_3 plants, but C_4 metabolism is inefficient in shady or cool environments. Less than 1% of earth's plant species can be classified as C_4.

Crassulacean acid metabolism plants

Crassulacean acid metabolism (CAM) plants (from "crassulacean acid metabolism", because this mechanism was first described in members of plant family Crassulaceae) are a different kind of C_4 plant. In the C_4 plants described above, the fixation of CO_2 into 4-carbon sugars and the further fixation of CO_2 into 3-carbon sugars happens in different cells, separated in space but at the same time. In CAM plants, the two different kinds of CO_2-fixation happen in the same cells, but separated in time. In CAM plants the fixation of CO_2 into oxaloacetate happens at night, when it is cooler and the stomata can open to ensure a plentiful supply of CO_2, and then the oxaloacetate is stored as malic acid. Then, during the day, the stomata close to minimize moisture loss, and the stored malic acid is reclaimed and turned back into CO_2 to power the normal Calvin cycle.

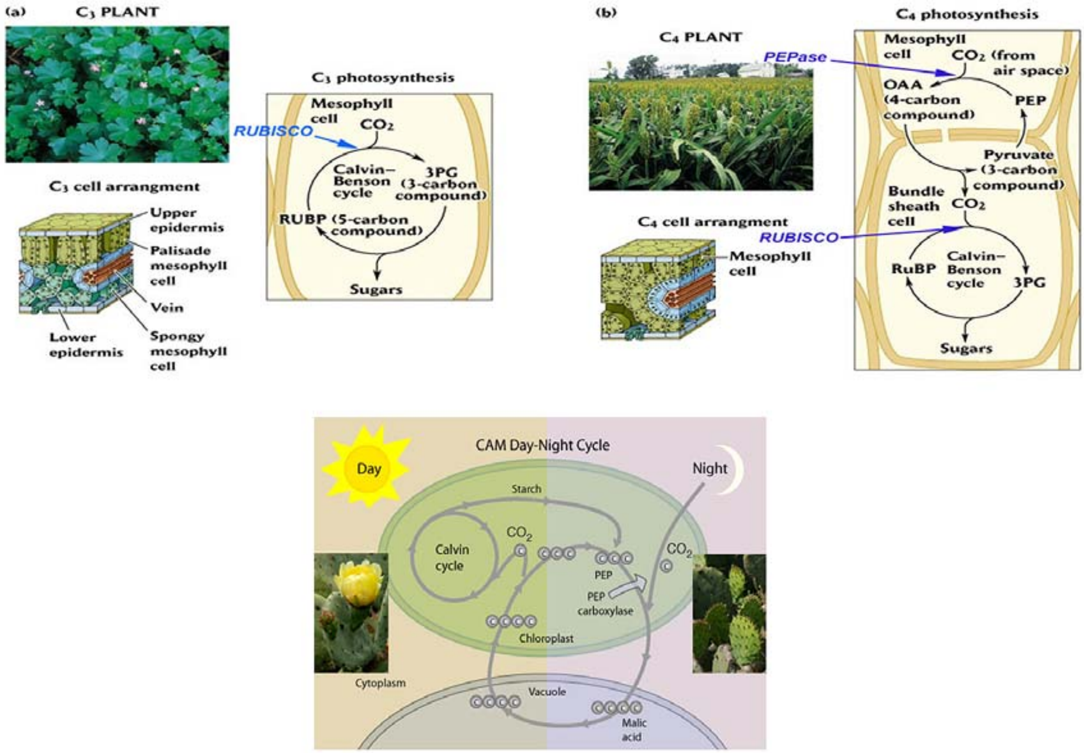


FIGURE 1. *Typical C_3 (a), C_4 (b) and CAM (c) plants with carbon fixing cycle (adapted from Salisbury & Ross, 1991)*

Single cell C_4 photosynthesis

It has been thought that a specialized leaf anatomy, is composed of two distinctive photosynthetic cell types (Kranz anatomy) is required for C_4 photosynthesis. C_4 photosynthesis can function within a single photosynthetic cell in terrestrial plants. *Borszczowia aralocaspica* (Chenopodiaceae) has the photosynthetic features of C_4 plants, yet lacks Kranz anatomy. This species accomplishes C_4 photosynthesis through spatial compartmentation of photosynthetic enzymes, and by separation of two types of chloroplasts and other organelles in distinct positions within the chlorenchyma cell cytoplasm. The most dramatic variants of C_4 terrestrial plants were discovered recently in two species, *Bienertia cycloptera* (Fig. 2a) and *Borszczowia aralocaspica* (Chenopodiaceae); each has novel compartmentation to accomplish C_4 photosynthesis within a single chlorenchyma cell (Fig. 2b and 2c). C_4 photosynthesis in terrestrial plants was thought to require Kranz anatomy because the cell wall between mesophyll and bundle sheath cells restricts leakage of CO_2. Recent work with the central Asian chenopods *Borszczowia aralocaspica* and *Bienertia cycloptera* show that C_4 photosynthesis functions efficiently in individual cells containing both the C_4 and C_3 cycles. These discoveries provide new inspiration for efforts to convert C_3 crops into C_4 plants because the anatomical changes required for C_4 photosynthesis might be less stringent than previously thought (Sage, 2002).

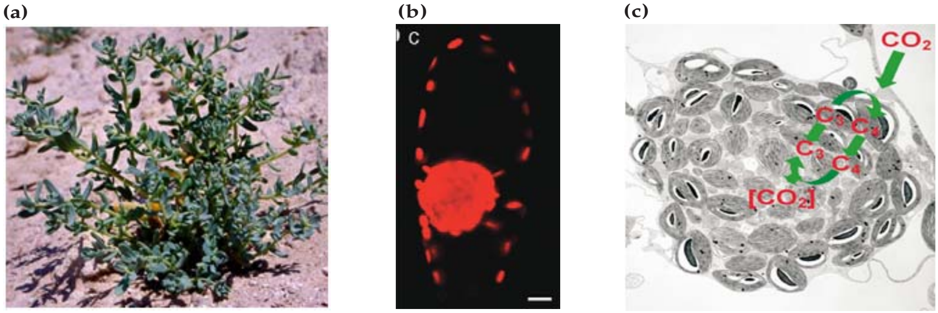


FIGURE 2. *(a) Bienertia cycloptera (Chenopodiaceae), (b)Confocal microscopy showing chloroplasts in two domains, in a central and in a peripheral cytoplasmic compartment, (c) Atmospheric CO_2 is fixed in to C_4 acids in the peripheral cytoplasmic compartment, where they are decarboxylated and the CO_2 fixed by rubisco. Adapted from Chuong et al. (2006) and Edward et al. (2004).*

Impact of climate change on agriculture and food supply

Will climate change help or hinder our efforts to maintain an adequate food supply for the increasing world population of the next century? Which regions are likely to benefit and which are likely to suffer food shortages and socioeconomic crises? Could the beneficial effects of increasing atmospheric CO_2 on plants (the so-called "CO_2 fertilization effect") counteract some of the negative effects of climate change? What types of adaptations and policies will be necessary to take advantage of the opportunities and minimize the negative impacts of climate change on agriculture? What will the cost of these adaptations and policies be? To address these questions, scientists from various disciplines have linked together climate, crop growth, and economic-food trade computer models. These multi-layered models are extremely complex and contain numerous assumptions about the physical, biological, and socioeconomic systems they attempt to simulate. Nevertheless, they represent the most comprehensive analyses we have at present. They can be useful to policymakers, particularly if there is an educated appreciation for the level of uncertainty inherent in their projections. Before presenting model outcomes, we will first review some fundamental aspects of what we know and don't know about how crop plants respond to temperature and increases in atmospheric CO_2.

Temperature effects on plants

Most plant processes related to growth and yield are highly temperature dependent. We can identify an optimum temperature range for maximum yield for any one crop. Crop species are often classified as warm- or cool-season types. The optimum growth temperature frequently corresponds to the optimum temperature for photosynthesis, the process by which plants absorb CO_2 from the atmosphere and convert it to sugars used for energy and growth. Temperature also affects the rate of plant development. Higher temperatures speed annual crops through their developmental phases. This shortens the life cycle of determinate species like grain crops, which only set seed once and then stop producing. The photosynthesis rate with temperature is shown in Fig. 3 for C_3 plants at today's CO_2 levels (Low CO_2), and at double CO_2 level (High CO_2). The upper curve is the same for C_4. From this it is clear that at double CO_2 concentration, not only has the efficiency of C_3 crops improved tremendously, but the temperature at which optimal photosynthesis occurs in C_3 increases up to that of C_4. Thus the vast majority of food crops will benefit hugely by increased CO_2, and even more so by increased CO_2 coupled with warming.

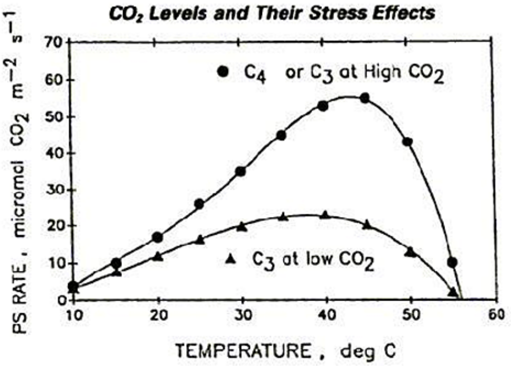


FIGURE 3. *Photosynthetic rate versus temperature for C_3 and C_4 leaves (Adapted from Taiz & Zeiger, 1991).*

Photosynthesis and elevated carbon dioxide

World food security depends on C_3 and C_4 photosynthesis. Less than 1% of all plant species in the world use the C_4 photosynthesis pathway. Of the 86 plant species that supply most of the world's food, only five use the C_4 photosynthetic pathway, of which only four are of much importance (corn, sorghum, millet, and sugarcane) yet these four constitute some 20% of all the food crops grown. Those crops using the C_3 pathway include nearly all cereals (wheat, rice, barley, oats, rye, triticale, etc.), all legumes (dry bean, soybean, peanut, mung bean, faba bean, cowpea, common pea, chickpea, pigeon pea, lentil, etc.), nearly all fruits (including banana, coconut, etc.), roots and tubers (potato, taro, yams, sweet potato, etc.). C_3 is also the pathway for sugar beet, for fibre crops (cotton, jute, etc.) and oil crops (sesame, sunflower, rapeseed, safflower, etc.), and for trees. At present atmospheric levels of CO_2, C_4 plants are more efficient at photosynthesis than C_3: in absolute conversion efficiency of light energy to stored chemical energy they are around 7% efficient, compared to 4% for C_3. C_4 plants typically use less water per weight of biomass produced, and can tolerate greater water and temperature stress than C_3 plants. Accordingly, C_4 crops are most often grown in tropical and equatorial regions. The advantage that C_4 plants have in terms of photosynthesis does not always translate into higher harvest yields, however, as only parts of the plant are edible. In terms of ground use, C_3 crops can produce some of the highest amounts of edible calories and protein per acre: for example, potatoes and soybeans, respectively.

C_4 plants show a relatively small improvement in photosynthesis rate with increasing atmospheric CO_2 above present levels; however, at increased levels of CO_2 the leaf pores (stomata) of both C_4 and C_3 plants increasingly close up, which also reduces the amount of water lost by the plant (transpiration). Thus C_3 and C_4 plants significantly improve their water use efficiency as CO_2 levels increase. This is shown in Fig. 4 for C_4 (corn) and C_3 (soybean). C_3 photosynthesis is less efficient than C_4 partly because of an effect known as photo-respiration, which results in the loss (to the atmosphere or soil) of a substantial proportion of the carbon that has been extracted from the atmosphere by photosynthesis. C_3 photo-respiration increases under heat stress and drought, which is a major factor behind the choice of C_4 crops for hot dry climates. However, as CO_2 levels increase, photo-respiration is suppressed, such that at double today's levels of atmospheric CO_2 the efficiencies of C_3 plants (in photosynthesis rate and water use) are as good as or better than C_4 plants (Fig. 5). Moreover, at higher levels of CO_2, C_3 plants can maintain efficient photosynthesis rates at considerably higher temperatures than today's conditions – their optimal temperatures for photosynthesis increase.

As CO_2 concentrations increase, the photosynthetic efficiency gap between C_3 and C_4 plants rapidly closes, and at double today's CO_2 concentration (i.e. at 780 ppm instead of today's 390 ppm), the photosynthesis rates are the same. Incidentally, the majority of the world's most troublesome weeds use the C_4 pathway, and so have a competitive advantage over C_3 crops at current CO_2 concentrations. At higher CO_2 concentrations, competing for the same resources on the same patch (light, water, CO_2, nutrients, etc.), C_3 crops increasingly out-compete the weeds.

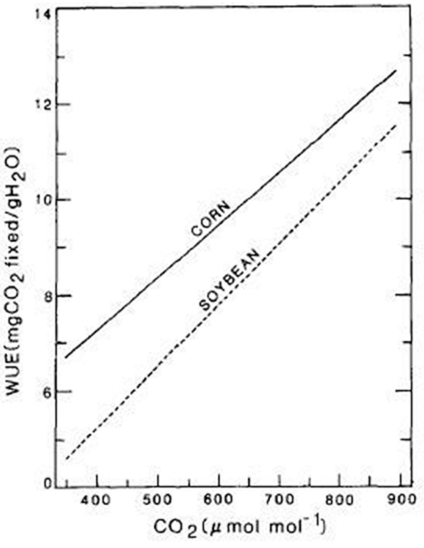


FIGURE 4. *Water use efficiency (WUE) for corn and soybean over a range of CO_2 concentration (Rogers et al., 1983).*

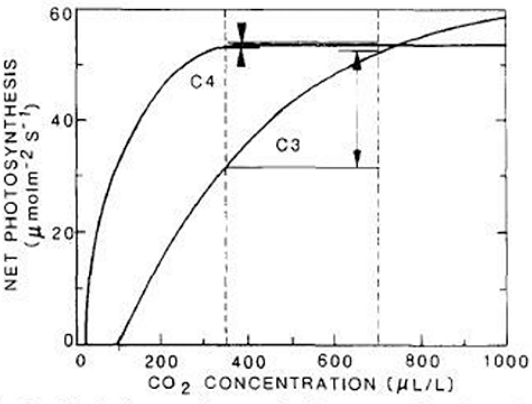


FIGURE 5. *PN Curve for C_3 and C_4 species (Taiz & Zeiger, 1991). Dashed vertical lines at 380 and 700 ppm mark the current CO_2 level & the doubled concentration predicted to be reached some time in the next century (Houghton et al., 1990). Arrow indicates incremental rise in net PN due to the CO_2 doubling (Kimball, 1983).*

Do C_3 and C_4 plants respond similarly to climate change?

Evidence suggests that C_4 plants produce greater amounts of biomass per unit of intercepted photosynthetically active radiation. This is due in large part to two factors. First, C_4 plants have a greater quantum yield than C_3 plants at 30°C (the C_4 advantage diminishes at lower temperatures and as atmospheric CO_2 partial pressures rise). Second, C_4 plants have greater rates of CO_2

assimilation per unit leaf nitrogen (this benefit diminishes as leaf area index and/or canopy nitrogen content increases). The protein cost of C_4 enzymes per unit chlorophyll is calculated and found to be similar to that of C_3 photosynthesis. However, the rate of CO_2 assimilation per unit nitrogen in C_4 plants is greater than that of C_3 plants because high CO_2 partial pressure in the bundle sheath cells enables rubisco to operate near its maximum catalytic rate and suppresses photorespiration. Rice leaf anatomy is examined with respect to locating the C_4 metabolism. Chloroplasts in bundle sheath cells represent only a minute fraction of those present in the rice leaf. In addition, whereas mesophyll cells are immediately adjacent to bundle sheath cells in terrestrial C_4 leaves, there are numerous mesophyll cells between adjacent veins in rice, which would diminish the efficiency of the C_4 cycle. To engineer the C_4 pathway into rice is therefore a formidable challenge. Rice is the most important food crop in the world. Major advances have occurred in rice production as a result of the wide-scale adoption of improved rice varieties. However, demand for rice in low-income countries continues to increase because of increases in the population of rice consumers and improvements in living standards. It is estimated that we will have to produce 50% more rice by 2025. To meet this challenge, we need rice varieties with higher yield potential. Several approaches are being employed for developing rice varieties with increased yield potential. These include population improvement, ideotype breeding, heterosis breeding, wide hybridization, genetic engineering, and molecular breeding.

Photosynthetic performance of transgenic rice plants overexpressing maize C_4 photosynthesis enzymes

C_4 plants such as maize and sorghum are more productive as compared to C_3 rice and wheat, because C_4 plants are 30-35% more efficient in photosynthesis. Matsuoka el al. (2001) tried to alter the photosynthesis of rice from C_3 to C_4 pathway by introducing cloned genes from maize which regulates the production of enzymes responsible for C_4 synthesis. Molecular cloning of C_4 specific Ppc (encoded phosphoenolpyruvate carboxylase, PEPcase) gene of sorghum and its high level expression in transgenic rice were studied by Fang et al. (2003). Characterization and functional analysis of phospho*enol*pyruvate carboxylase kinase genes in rice was done by Fukayama et al. (2006). Nomura et al. (2005) studied the differential expression pattern of C_4 bundle sheath expression genes in rice. Fukayama et al. (2003) studied the activity regulation and physiological impacts of the maize C_4-specific phospho*enol*pyruvate carboxylase over production in transgenic rice plants. Hiroko et al. (2001) studied the high level expression of C_4-specific NADP-malic enzyme (NADP-ME) in leaves and impairment of photoautotrophic growth in a C_3 plant, rice. The chloroplastic NADP-ME is a key enzyme of the C_4 photosynthesis pathway in NADP-ME type C_4 plants such as maize. To express the chloroplastic NADP-ME in leaves of a C_3 plant, rice, full-length cDNAs encoding the rice C_3-specific isoform and the maize C_4-specific isoform of the enzyme were expressed under the control of the rice *Cab* promoter. Transformants carrying the rice cDNA showed the NADP-ME activities in the leaves less than several-fold that of non-transformants, while those carrying the maize cDNA showed activities up to 30-fold that of non-transformants or about 60% of the NADP-ME activity of maize leaves. These results indicate that expression of the rice C_3-specific NADP-ME is suppressed at co- and/or post-transcriptional levels by some regulation mechanisms intrinsic to rice, while that of the foreign C_4-specific isoform can escape from such suppression. The accumulation of the maize C_4-specific NADP-ME led to bleaching of leaf color and growth hindrance in rice plants under natural light. These deteriorative effects resulted from enhanced photoinhibition of photosynthesis due to an increase in the level of NADPH inside the chloroplast by the action of the maize enzyme (Hiroko et al., 2001). C_3 plants including many agronomically important crops exhibit a lower photosynthetic efficiency due to inhibition of photosynthesis by O_2 and the associated photorespiration. C_4 plants had evolved the C_4 pathway to overcome low CO_2 and photorespiration. Introduction of the maize intact phosphoenolpyruvate carboxylase gene (*Ppc*) caused 30-100 fold higher PEPC activities than non-transgenic rice. These results demonstrated that intact C_4-type genes are available for high level expression of C_4 enzymes in rice plants (Matsuoka et al., 1998). Pyruvate orthophosphate dikinase (*Pdk*) is another key enzyme in C_4 photosynthesis. Based on the results with transgenic rice plants, it was demonstrated that the regulatory system controlling the *Pdk* expression in maize is not unique to C_4 plants but rice (C_3 plant) posses a similar system. C_4 photosynthesis is advantageous when limitations on carbon acquisition are imposed by high temperature, drought and saline conditions.

Transgenic rice plants overexpressing maize C_4-specific phosphoenolpyruvate carboxylase (PEPC) exhibit a higher photosynthetic rate (up to 30%) and a more reduced O_2 inhibition of photosynthesis than untransformed plants. There is a small increase in the amount of atmospheric CO_2 being directly fixed by PEPC. Similarly, transgenic rice plants overexpressing the maize chloroplastic pyruvate, orthophosphate dikinase (PPDK), also have higher photosynthetic rates (up to 35%) than untransformed plants. This increased photosynthetic capacity is at least in part due to an enhanced stomatal conductance and a higher internal CO_2 concentration. By using conventional hybridization, integration of maize PEPC and PPDK genes into the same transgenic rice plants. In the segregating population, the photosynthetic rates of plants with high levels of both maize enzymes are up to 35% higher than those of untransformed plants. Under full-sunlight conditions, the photosynthetic capacity of field-grown PEPC transgenic rice plants is twice as high as that of untransformed plants. PEPC transgenic plants consistently have a higher photosynthetic quantum yield by photosystem II and a higher capacity to dissipate excess energy photochemically and nonphotochemically. Preliminary data from field tests show that the grain yield is about 10-30% higher in PEPC and 30-35% higher in PPDK transgenic rice plants relative to untransformed plants. Taken together, these results suggest that introduction of C_4 photosynthesis enzymes into rice has a good potential for enhancing the crop's photosynthetic capacity and yield.

C_3 versus C_4 photosynthesis in rice

C_4 photosynthesis confers substantial benefits upon herbaceous plants in tropical environments, most notably in high-light habitats with frequent drought, heat, and salinity stress. In flooded situations, it is less beneficial, for reasons that are not clear. Conditions in wetlands may not enhance CO_2 assimilation rates of C_4 plants to the degree needed to suppress C_3 competitors; alternatively, wetland C_3 plants may be well adapted for marshy environments for reasons unrelated to photosynthetic pathway. If the wetland condition prevents C_4 dominance because C_3 photosynthetic performance is relatively strong in flooded soils, then the development of C_4 rice would probably be of significant benefit in upland situations only, particularly those that experience drought. Alternatively, if C_4 plants are less well adapted to flooded conditions than C_3 plants for reasons unrelated to photosynthetic pathway, then substantial benefits may result from introducing C_4 rice plants into flooded soils. In either case, these considerations must be evaluated in the context of future levels of atmospheric CO_2. Elevated CO_2 will enhance photosynthetic efficiency and yield of C_3 rice plants, perhaps more than might be obtained with C_4 rice. Existing rice varieties may not be adapted to fully exploit the increased productive potential that high CO_2 represents, and thus engineering C_3 rice for a CO_2-enriched environment may be an important way to enhance yield. For example, current varieties of rice plants grown at high CO_2 contain too much rubisco, and reduction of rubisco content by antisense technology can further enhance yield and resource-use efficiency. Because the high CO_2 levels favoring C_3 over C_4 photosynthesis may not appear for many decades, however, the C_4 strategy may be the best approach for increasing rice production in the next century.

Will increased photosynthetic efficiency lead to increased yield in rice?

Plant mass is primarily derived from photosynthesis and so it is surprising that final plant mass (yield) and photosynthetic rate of leaves are often not well correlated. The rate of plant respiration and loss of plant matter through detachment also influence yield. The lack of correlation also reflects the fact that photosynthate availability is just one of many signals that affect plant growth and development. Plants grown in elevated CO_2 normally have increased yield, which tells us that increasing the availability of photosynthate is likely to increase yield, though perhaps not as much as might be expected. In redesigning photosynthesis for increased yield, we can focus on the inputs, fundamental mechanisms, or outputs. Given the importance of the relationship between photosynthesis and plant growth, which focuses on the outputs of photosynthesis and their immediate use, especially the enzyme sucrose-phosphate synthase (SPS). Plants that are transformed to express more sucrose-phosphate synthase sometimes have higher yields than untransformed plants. Two hypotheses were tested to explain this variability in response: (1) Does expression of the gene in nonphotosynthetic tissue affect yield? (2) Is there an optimum level of SPS that should be sought? It was found that expression in nonphotosynthetic tissue was not important but that there was an optimum level of SPS activity. Too much or too little of this enzyme results in lowered yield and it may be that most plants have a level appropriate to the preindustrial atmospheric CO_2 concentration or a level that results in a more conservative strategy than is required for crop plants. C_4 plants, including maize and sorghum, have been employed to elucidate the molecular mechanisms and signaling pathways that control C_4 photosynthesis gene expression. Current evidence suggests that C_4 photosynthesis is advantageous when limitations on carbon acquisition are imposed by high temperature, drought and saline conditions. It has been thought that a specialized leaf anatomy, composed of two, distinctive photosynthetic cell types (Kranz anatomy) are required for C_4 photosynthesis. There are evidence that C_4 photosynthesis can function within a single photosynthetic cell in terrestrial plants. *Borszczowia aralocaspica* and *Bienertia cycloptera* (Chenopodiaceae) have the photosynthetic features of C_4 plants, yet lacks Kranz anatomy. These species accomplish C_4 photosynthesis through spatial compartmentation of photosynthetic enzymes, and by separation of two types of chloroplasts and other organelles in distinct positions within the cell cytoplasm.

The single cell C_4 photosynthetic system has given us the impetus that it may be experimentally feasible to genetically engineer all C_4 genes in single cell of C_3 plants i.e. rice to enhance its photosynthetic activity and productivity. Our concept in transferring the genes from single cell C_4 photosynthesis system envisages to overexpress phosphoenolpyruvate carboxylase (PEPcase) and carbonic anhydrase (CA) in cytosol, and target pyruvate orthophosphate dikinase (PPDK), NADP-Malate dehydrogenase (NADP-MDH) and NADP-ME to chloroplasts of C_3 plants using appropriate promoters and vectors. This may lead to improved CO_2 concentrating mechanism in a single cell favouring carboxylation over that of oxygenation function of rubisco.

Conclusions

The three major uncertainties regarding impacts of climate change on agriculture are: (1) the magnitude of regional changes in temperature and precipitation; (2) the magnitude of the beneficial effects of higher CO_2 on crop yields; and (3) the ability of farmers to adapt to climate change. Many crop models account for the CO_2 effect by globally increasing yields of C_3 crops by 20 - 35%, which assumes a near optimum growth environment. Field conditions are seldom optimum, but farmers with access to adequate water, fertilizer, and other inputs will likely gain more from a CO_2 doubling than farmers who do not have these resources. The C_4 rice with higher photosynthetic efficiency in hotter environment, higher water and nutrient use efficiency could be one adoption option in the face of climate change. The present knowledge though inadequate, can build up further for perfecting C_4 rice.

References

Chuong, S.D.X., Franceschi, V.R., & Edward, G.E. (2006). The cytoskeleton maintains organell partitioning required for single-cell C_4 photosynthesis in *Chenopodiaceae* species. *Plant Cell,* 18, 2207-2223.

Edwards, G.E., Franceschi, V.R., & Voznesenskaya, E.V. (2004). Single-cell C_4 photosynthesis versus the dual-cell (*Kranz*) paradigm. *Annual Review in Plant Biology,* 55, 173-196.

Fang, Z., ChiWei, wangQiang, ZhangQide & WunNaihu. (2003). Molecular cloning of C_4 specific Ppc gene of sorghum and its high level expression in transgenic rice. *Chinese Science Bulletin*, 48, 1835-1840.

Fukayama, H., Hatch, M.D., Tamai, T., Tsuchida, H., Sudoh, S., Furbank, R.T., & Miyao, M. (2003). Activity regulation and physiological impacts of the maize C_4-specific phospho*enol*pyruvate carboxylase overproduced in transgenic rice plants. *Photosynthic Research,* 77, 227-239.

Fukayama, H., Tamai, T., Sullivan, S., Miyao, M., & Nimmo, H.G. (2006). Characterization and functional analysis of phospho*enol*pyruvate carboxylase kinase genes in rice. *Plant Journal,* 47, 258-268.

Hiroko Tsuchida, Tesshu Tamai, Hiroshi Fukayama, Sakae Agarie, Mika Nomura, Haruko Onodera, Kazuko Ono, Yaeko Nishizawa, Byung-Hyun Lee, Sakiko Hirose, Seiichi Toki, Maurice S. B. Ku, Makoto Matsuoka, & Mitsue Miyao. (2001). High level expression of C_4-specific NADP-malic enzyme in leaves and impairment of photoautotrophic growth in a C_3 plant, rice. *Plant and Cell Physiology*, 42, 138-145.

Houghton, J.T., Jenkins, G.J., & Ephraums, J.J. (Eds.). (1990). *Climate change*: *The IPCC scientific assessment.* (p. 365). World Meteorological Organization, United Nations Environmental Programme, Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Kimball, B.A. (1983). Carbon dioxide and agricultural yield: An assemblage and analysis of 770 prior observations. WCL Report 14. (p.716). US Dept. of Agriculture, *Agriculture Research Services*, Arizona: Phoenix.

Matsuoka, M., Nomura, M., Agarie, S., Miyao-Tokutomi, M., & Ku, M.B.S. (1998). Evolution of C_4 photosynthetic genes and overexpression of maize C_4 genes in rice. *Journal of Plant Research,* 111, 333-337.

Matsuoka, M., Fukayama, H., Ku, M.B.S., & Miyao, M. (2001). High level expression of C_4 photosynthetic genes in transgenic rice. In G.S. Khush, D. S. Brar, B. Hardy (Eds.), *Rice genetics*. Volume IV. (pp. 439-447). Los Banos, Philippines: International Rice Research Institute.

Nomura, M., Higuchi, T., Ishida, Y., Ohta, S., Komari, T., Imaizumi, N., Miyao-Tokutomi, M., Matsuoka, M., & Tajima, M. (2005). Differential expression pattern of C_4 bundle sheath expression genes in rice, a C_3 plant. *Plant Cell Physiology,* 46, 754-761.

Rogers, H.H., Thomas, J.F., & Bingham, G.E. (1983). Response of agronomic and forest species to elevated atmospheric carbon dioxide. *Science,* 220, 428-429.

Sage, R.F. (2002). How terrestrial organisms sense, signal and respond to carbon dioxide. *Integrative and Comparative Biology*, 42, 469-480.

Salisbury, F.B., & Ross, C.W. (1991). *Plant physiology* (4th ed.). (pp.682). Belmount, California: Wadsworth Publishing Company.

Taiz, L., & Zeiger, E. (1991). *Plant physiology*. (pp. 559). Redwood City, California: The Benjamin and Cummings Pub. Co.

*****

Chapter 15

Rice quality: A matter of concern in climate change scenario

S.G. Sharma
Central Rice Research Institute, Cuttack, Odisha, India
e-mail: sgsharmacrri@yahoo.co.in

Rice is an integral part of the diet of about half of the global population and accounts for 35-75% of the calories consumed by more than three billion Asians (Khush, 2007). About 100,000 rice accessions are preserved in the gene bank of the International Rice Research Institute (IRRI), Philippines. The Central Rice Research Institute, Cuttack has a collection of about 30,000 rice germplasm. At present, thousands of rice varieties and land races are grown in the world. Proper water and nutrient management practices and pest (insect, weed, and pathogen) control measures add not only to grain yield but also to grain quality. Today, India is self sufficient in rice production and stands among the top three exporters of rice. Thus, the current focus is on improving quality of rice with respect to grain characteristics and nutritional value as the consumers now demands quality rice. But in view of the changing climate scenario, emphasis has also to be given to understand the impact of global warming and rising levels of greenhouse gases in the atmosphere on rice grain quality. Rice grain quality is a complex issue and needs to be understood well, before we deliberate upon the effect of climate change on it.

Concept of quality

The concept of rice grain quality varies with the consumer preference and the purpose (end use). The term 'rice grain quality' refers to the visual (physical) characteristics and chemical composition, which decide the marketing quality, cooking and eating quality and the nutritional quality. Thus, normally, grain size, shape and appearance, milling and cooking characteristics are the main determinants of quality. Nutritional quality is also an integral part of rice grain quality. Grain quality is basically a varietal trait and thus depends on its genetic constitution, but cultural practices, environment and post harvest practices play an important role in shaping the final product. The issue of rice grain quality is complicated by the fact that it is the individuals who decide what kind of rice they want; and since taste/likings differ from region to region, the job of the rice scientist, that is, to translate the consumer preference for quality (visual, cooking eating, etc.) into measurable physical and chemical parameters which can be ultimately traced to a particular gene(s), becomes more difficult. Grain quality characteristics assume more importance for rice compared to other food grains; they are the prime determinants of market price because most of the rice (almost 95%) is consumed as *cooked whole grain*.

Processing of paddy

The crop is harvested as paddy or rough rice at 20-22% grain moisture with the mature rice grain (caryopsis) enclosed within an inedible cover called hull or husk. Paddy is dried to a moisture content of 12-14% before processing and to12%, if it is to be preserved for seed purpose. It takes about 3-4 months (ageing period) for the grain quality characters to stabilize, hence paddy grains are analyzed for quality parameters after at least 3 months of harvest.

Milling quality

The paddy is made free of immature grains, dockage and brought to 14% moisture level before further processing. It is now dehulled through rubber rollers to minimize breakage of grains to obtain 'brown rice' which has a colored (pink, brown, red blue, black) coating that is rich in vitamins, minerals, oil and other nutrients and is thus prone to infestation by insects and microbes. When the brown rice is passed through an abrasive whitening machine the colored coat is removed as brownish powder called *bran* and white rice grains called *milled rice* .It is further passed through a friction type whitening machine resulting into a smooth final product called *polished rice* which we are used to eat. Milling is done to remove bran and germ with minimum breakage of whole grain. It is produced commercially by millers because it has longer shelf life and has a better appearance than the brown rice but the latter is better in nutritive value than the former. Thus, normally, it is the milled rice characteristics we refer to while describing grain quality. Rice kernel with 75% or more of the average length of the whole kernel is called head rice. Percentage of head rice recovered during milling of paddy is called milling yield or head rice recovery (HRR). High milling yield (> 60%) is the first condition for a variety to be successful. For long slender grains it may be between 55-60%. The sum total of the amounts of head rice and broken rice obtained from a paddy sample is called milling recovery which is generally about 70%. The millers prefer rice with high percentage of hulling, milling and HRR. The HRR is the single most important factor that determines market price of rice as it is normally eaten as whole grain.

Physical characteristics: Grain size and shape

As rice is consumed mainly as cooked whole grain, size and shape become important and are now-a-days measured with an image analyzer. These are important criteria of rice quality to develop new varieties and also for trade. Different countries still have their own classification of rice grains. In India, Ramiah's classification (Govindaswami, 1985) is followed to categorize grains and is given below:

TABLE 1. *Rice grain classification followed in India*

Grain type	Milled grain length (mm)	Length: breadth ratio
Long slender (LS)	≥ 6 mm	≥ 3.0
Short slender (SS)	< 6 mm	≥ 3.0
Medium slender (MS)	< 6 mm	2.5 to 3.0
Long bold (LB)	≥ 6 mm	< 3.0
Short bold (SB)	< 6 mm	< 2.5

Features of quality rice

Quality means different things to different people depending on their eating preferences and specific requirement. However, medium/ long slender and translucent grains with high HRR, good cooking and eating quality (good elongating ability during cooking, tender, well separated grains, good mouth feel) and pleasant aroma are normally preferred. The desirable features in quality rice normally include right shape (MS, LS), translucency, no chalk, no cracks, high HRR%, excellent cooking properties (well separated grains, soft texture), good elongation ratio (ratio of lengths of cooked and uncooked grain), no color and good aroma (in scented rice).

Chalk

Grains with opaque areas (white belly, white centre, white back) in the endosperm caused due to loose packing of single starch granules and protein molecules is an undesirable trait (although Italians like it) as the chalky grains show more breakage on dehulling and milling compared to translucent grains and absorb more water (due to air spaces) during cooking resulting in soft cooked rice. Grain chalkiness is greatly affected by environmental conditions during cultivation. In some seasons, cracking of the rice grain is a significant problem. Most cracking occurs in the field and seems to be related to changes in grain moisture or to moisture cycles after the rice matures. Cracking may also result from rain on dry grain and storage of grain with variable moisture levels. It decreases HRR because cracked grains often break during milling and reduce payments received by the grower and the miller. Cracking also decreases the cooking quality of the grain. Rough handling of grain during harvest operations and during drying and processing will also cause the grain to crack. The marketing quality depends on appearance (length, breadth, HRR, chalkiness, color, dockage and packaging).

Cooking Quality

The first indicator of good cooking quality of rice is that the cooked grain retains a firm shape and does not disintegrate during or after cooking. Varieties that do not meet this requirement are not commercially successful. The cooking quality is mainly governed by the packaging of starch molecules and the amylose: amylopectin ratio, since starch forms the major part (about 90%) of rice kernel. The cooking quality is determined by alkali spreading value (ASV), gelatinization temperature (GT), water uptake (WU) value , volume expansion ratio (VER), kernel length after cooking (KLAC), elongation ratio (ER), gel consistency (GC) and apparent amylose content (AC).

Alkali spreading value: The ASV is measured by treating six rice grains in a petri plate with 10 ml of 1.7% KOH for 23 hours at 30°C and looking for disintegration of grains, on a 1-7 scale.

Gelatinization temperature: The temperature at which the starch granules swell in water irreversibly losing their crystallinity) is indicated by alkali digestion. It ranges from 55-79°C. Gelatinization temperature is high for high amylose rice but then low amylose rices have also been found to have high GT. The waxy or low amylose rices have more free sugars and maltodextrins giving it sweetness. The differential scanning calorimetry (DSC) gives the accurate measure of GT rather than ASV. The ASV and GT are also used as indicators of digestibility of a rice grain.

Water uptake value: The WU is a measure of the volume of water absorbed by 100g of grains.Volume expansion ratio is a measure of the increase in volume of rice after cooking. Kernel length after cooking and elongation ratio (mean length of ten cooked rice grains divided by mean length of the raw milled grains) measure lengthwise elongation during cooking. Gel consistency measures the tendency of cooked rice to harden on cooling, especially for high amylose rices. Rices with soft GC cook tender and remain soft even upon cooling and hence are preferred by consumers and are a priority for breeding programme.

Apparent amylose content : As the cooking and eating quality is determined mainly by amylose content, all rice improvement programs include amylose content as a parameter which is normally measured by the iodine binding capacity (IBC) although other methods like near infra red (NIR) grain analyzer, size exclusion chromatography (SEC) and nuclear magnetic resonance (NMR) are also used.

Nutritional quality

Rice is the staple food for half of the people on the earth. Being a cereal crop, it is rich in starch, contains little fat and on an average 7% protein of excellent quality. Milled rice contains more than 80% carbohydrates, which include mainly sugars and starch. In general, a low ambient temperature during grain filling results in increased amylose content in rice and *vice-versa*. The high amylose rice shows high volume expansion and flakiness. The cooked grains are dry, less tender and become hard upon cooling whereas the low amylose rice cooks soft and sticky. The intermediate amylose rice is normally preferred the world over except the places where *japonica* is liked. Milled rice normally contains about 7% total protein though some grains contain up to 16% protein. The brown rice contains up to 2.8% lipids. Milled rice has 0.64% lipid and the rice bran contains 19% lipids, from which oil is extracted. Brown rice is richer in minerals compared to milled rice. Milling reduces percentage of P (0.28 to 0.06), K (0.21 to 0.05), Mg (0.10 to 0.015), Ca (0.013 to 0.008), Mn (17.7 to 5 ppm), Fe (12 to 5 ppm), Zn (27 to 16 ppm) and Cu (3 to 2.5 ppm). Brown rice has more amounts of vitamins than the milled rice because they are present mainly in bran. Most of them are lost to different degrees during milling and subsequent washing. Rice is a good source of vitamin E (tocopherols) and tocotrienols. The vitamins A, C and D are not present in rice. Basmati rices and the small or medium grain non-basmati rices have pleasant aroma and are classified under quality rices. The aroma of scented rice is mainly due to 2-acetyl 1-pyrroline (2-AP). Basmati rice contains about 0.09 ppm of 2-AP which is about 12 times more than that present in non-aromatic rices. The 2-AP content is measured with a GC-MS. For screening, freshly cooked rice is subjected to a sniff test in a test tube or raw rice is digested with dilute alkali. High temperature is most likely to reduce the 2-AP content in scented rices particularly the basmati rices, as the aroma compound is volatile in nature.

Climate change and rice grain quality

The shadows of climate change is looming large on our planet. Rising levels of greenhouse gases and increasing atmospheric temperature have already begun to exert adverse effect on global climate. Carbon dioxide (CO_2) level and temperature are two vital factors whose interaction will greatly determine the over all effect of climate change on agriculture in terms of quality as well as quantity of the produce. In India, a National Network Project titled 'Impact, Adaptation, and Vulnerability of Indian Agriculture to Climate Change' with an outlay of Rs. 422 crores has been launched with a focus on impacts of climate change on different sectors of agricultural production.

Carbon dioxide is essential to plant growth. Atmospheric CO_2 has increased about 35% since 1800 (from 280 to 380 parts per million [ppm]), and computer models predict that it will reach between 530 and 970 ppm by the end of the century (IPCC, 2007). Currently, its amount in the atmosphere is 380 ppm, compared to oxygen (210,000 ppm). Increased CO_2 is expected to have positive physiological effects by increasing the rate of photosynthesis. The effect of an increase in CO_2 would be higher on C_3 crops (like rice) than on C_4 crops (such as maize), because the former is more susceptible to CO_2 shortage. Thus, rising CO_2 concentration in the atmosphere can have both positive and negative consequences. Though there are some studies made on predicting the effect of climate change on the yield of important crops, studies on quality aspect are very few. Rice quality has the potential to change with elevated CO_2 levels, both alone and with increased temperature. High temperatures during the grain filling period are known to impede on the rice quality.

Chalkiness and environment

The endosperm of waxy rice is opaque but sometimes the endosperm of even the commonly eaten non- waxy rice grains also has opaque areas in an otherwise translucent grain. Such grains are called chalky grains which break easily during hulling/ milling resulting in poor market price. Chalkiness in the endosperm is caused due to loose packing of single starch granules and protein molecules and is thus an undesirable trait. Though basically a varietal character, chalkiness is greatly affected by environment.

Chalkiness and high temperature

There were varieties in the Philippines that were rarely chalky. Their panicles had very few secondary branches, indicating that panicle architecture is under genetic control and these genes play a role in chalk. It was reported by Resurreccion and Fitzgerald (2007) that high temperature reduces the time for which the panicle serves as sink. The grains on primary branches are of highest priority in the panicle and are translucent whereas grains on secondary branches are of lowest priority. As the supply of sugars from vegetative parts to panicle (sink) ceases the grain filling stops resulting in immature or chalky grains. Therefore, varieties with large panicles and high number of secondary branches (like IR 8) is more likely to form chalky grains when environmental conditions such as high temperature shortens the grain filling period (time for which panicle act as a sink) compared to those with a small panicle with fewer secondary branches (e.g., IR 60). The issue assumes importance in view of the present trend towards global warming. A single recessives gene *pgwc-8* (percent grains with chalkiness) is identified which controls chalkiness.

Chalkiness and atmospheric carbon dioxide levels

In elevated CO_2 , the proportion of grains containing a high amount of chalk per grain will decrease, which will increase the market value of the grain and may help to alleviate the burden of climate change on rice farmers. As environmental conditions affect starch content, the climate change is likely to affect chalk, amylose and GT. The positive effect of high CO_2 are not likely to compensate for negative effects of high temperature on grain quality. With a temperature rise of just 2°C sufficient to trigger the trait, researchers have noted that a 4°C increase could ruin entire crops, except for particular uses such as *risotto* and *sake*.

Experiments were done with rice plants grown at 26°C and 33°C. It was found that at the higher temperature, plants had only half as many days in which to make grain (14 compared with 30).Thus the time devoted to grain production is reduced by high temperature. At one extreme, the plant attempts to fill all grain, resulting in high yields of low-quality, chalky rice. At the other end, the plant sacrifices half the grain, resulting in low yields of high-quality grain. Variation in this stress response was also found to be under genetic control. Thus, scientists suggest for minimizing secondary branching in the panicle, extend the time available for grain filling, and select for a heat-stress response that avoids chalking.

Climate change: Amylose content, gel consistency and gelatinization temperature

Amylose content of rice grain, a major determinant of cooking quality is increased under elevated CO_2 conditions. Thus, cooked rice grain from plants grown in high-CO_2 environments in future would be firmer than that from plants grown today. When the quality traits of varieties grown in four combinations of temperature and CO_2 levels were assessed (Zhong et al., 2009) the negative impact of temperature on grain quality was unable to be overcome by an increase in CO_2. Four cultivars with different amylose content (AC) were subjected to two temperature treatments, referred as optimum (mean daily air temperature, 22°C) and high (32°C) temperature regimes starting from flowering stage until maturity. Effect of high temperature on AC and GC in milled rice was found to be cultivar-dependent. Under high temperature, AC increased for cv. Jiayu353 and remained little changed for cv. Guangluai4, which had intrinsically higher AC, and decreased for cv. Zhefu49 and cv. Jiazao935, which had lower AC. By contrast, high temperature reduced or kept stable GC values for cultivars with higher AC and increased GC values for those with lower AC. Moreover, high temperature significantly increased the GT of all cultivars. Pasting profiles and X-ray diffraction pattern of rice were also affected by temperature. The results suggest that high temperature during grain filling change the component and crystalline structure of starch and result in deterioration of eating and cooking quality for early-season *indica* rice.

Climate change: Protein, iron and zinc content of rice grains

Rising atmospheric concentrations of CO_2 could dramatically influence the performance of crops, but experimental results have been highly variable. For example, when C_3 plants are grown under CO_2 enrichment, productivity increases dramatically at first. But over time, organic nitrogen in the plants decreases and productivity diminishes in soils where nitrate is an important source of this nutrient. In C_3 plants, elevated carbon dioxide concentrations inhibit photorespiration, which in turn inhibits shoot nitrate assimilation. Thus, agriculture would benefit from the careful management of nitrogen fertilizers, particularly those that are ammonium based. Many crops depend on nitrate as their primary nitrogen source. As atmospheric CO_2 concentrations rise and nitrate assimilation diminishes, these crops will be depleted of organic nitrogen, including protein, and food quality will suffer.

Wheat, rice and potato provide 21, 14 and 2%, respectively, of protein in the human diet (FAOSTAT, 2007). Grain protein in rice (Terao et al., 2005) declined by about 10% at elevated CO_2 concentrations. Similarly, at elevated CO_2 and standard fertilizer levels, wheat had 10% less grain protein (Fangmeier et al., 1999; Kimball et al., 2001). Several approaches could mitigate these declines in food quality under CO_2 enrichment. Increased yields may compensate to some degree for total protein harvested. Several-fold increases in nitrogen fertilization could eliminate declines in food quality (Kimball et al., 2001), but such fertilization rates would not be economically or environmentally feasible given the anticipated higher fertilizer prices and stricter regulations on nitrate leaching and nitrous oxide emissions.

Greater reliance on ammonium fertilizers and inhibitors of nitrification (microbial conversion of ammonium to nitrate) might counteract food quality decreases. Nevertheless, the widespread adoption of such practices would require sophisticated management to avoid ammonium toxicity, which occurs when plants absorb more of this compound than they can assimilate into amino acids and free ammonium then accumulates in their tissues. Several of these issues might be simultaneously addressed by fertigation, or frequent additions of small amounts of ammonium-based fertilizers in water delivered through micro- irrigation. Moreover, the protein content of the grain decreases under combined increases of temperature and CO_2 (Ziska et al., 1997). Studies have shown that higher CO_2 levels lead to reduced plant uptake of nitrogen (and a smaller number showing the same for trace elements such as zinc) resulting in crops with lower nutritional value . However, concentrations of iron and zinc, which are important for human nutrition, would be lower under high temperature stress (Seneweera & Conroy, 1997).This would primarily impact on populations in poorer countries less able to compensate by eating more food, more varied diets, or possibly taking supplements.

In grains of two *japonica* rice varieties Koshihikari and Sasanishiki , the sucrose synthase activity was higher than that of invertase which was significantly correlated with starch accumulation rate, indicating that the sucrose synthase played an important role in sucrose degradation and starch synthesis. Under high temperature, the significant increase in grain sucrose content without any increase in fructose and glucose contents, suggested that the high temperature treatment enhanced sucrose accumulation, while diminished sucrose degradation in rice grains(Li Tian et al., 2005).

Conclusions

To summarize, the traits of physical quality of grain include length, width, uniformity, weight, head rice yield, color (whiteness and translucence), chalk, and cracks. The cooking and eating characteristics of rice are determined by amylose content, gelatinization temperature, viscosity, texture of cooked rice, flavor and aroma. The nutritional quality depends on the chemical composition. Most of these rice grain quality characteristics are likely to be adversely affected by the climate change and global warming. The rise in CO_2 could potentially be mitigated by crop plants, in which photosynthesis converts atmospheric CO_2 into carbohydrates and other organic compounds. The extent of this mitigation remains uncertain, however, due to the complex relationship between carbon and nitrogen metabolism in plants.

References

Food and Agriculture Organization Statistics (FAOSTAT). (2007). *Agricultural Data*. Italy: Food and Agricultural Organization of the United Nations.

Fangmeier, A., De Temmerman, L., & Mortensen, L. (1999). Effects of nutrients on grain quality in spring wheat crops grown under elevated CO_2 concentrations and stress conditions in the European, multiple-site experiment 'ESPACE-wheat'. *European Journal of Agronomy,* 10, 215-229.

Govindaswami, S. (1985). Post harvest technology: Quality features of rice. In S.Y. Padmanabhan (Ed.), *Rice research in India.* (pp. 627-642). New Delhi: ICAR.

IPCC (2007). *Climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change.* Cambridge and New York: Cambridge University Press.

Khush, G.S. (2007). Rice Breeding for the 21st century. In P.K. Aggarwal, J.K. Laddha, R.K. Singh, C. Devakumar, B. Hardy (Eds.), *Science, technology and trade for peace and prosperity*. Proceedings of the 26th International Rice Research Conference, 9-12 Octobr, 2006, New Delhi, India. (p. 782). India: Mc Millan, IRRI, ICAR and NAAS.

Kimball, B.A., Morris, C.F., & Pinter, P.J. (2001). Elevated CO_2, drought and soil nitrogen effects on wheat grain quality. *New Phytologist,* 150(2), 295-303.

Li, Tian., Liu, Qi-hua1., Ryu, Ohsugi., Tohru, Yamagishi., & Haruto, Sasaki. (2006). Effect of high temperature on sucrose content and sucrose cleaving enzyme activity in rice grain during the filling stage. *Rice Science,* 13(3), 205.

Resurreccion, A., & Fitzgerald, M. (2007). Chalk – A perennial problem of rice. In *Abstracts of the proceedings of the meeting of International Network for Quality Rice (INQR) on clearing old hurdles with new science: Improving rice grain quality*. (pp.9-10). Manila: IRRI.

Seneweera, S.P., & Conroy, J.P. (1997). Growth, grain yield and quality of rice (*Oryza sativa* L.) in response to elevated CO_2 and phosphorus nutrition. *Soil Science and Plant Nutrition,* 43, 131–1136.

Terao, T.S., Miura, T., & Yanagihara, T. (2005). Influence of free-air CO_2 enrichment (FACE) on the eating quality of rice. *Journal of Science and Food Agriculture,* 85, 1861-1868.

Zhong, L.J.F.M., Cheng, X., Wen, Z., Sun, X., & Zhang, G.P. (2009). The deterioration of eating and cooking quality caused by high temperature during grain filling in early-season *indica* rice cultivars. *Journal of Agronomy and Crop Science***,** 191(3), 218-222.

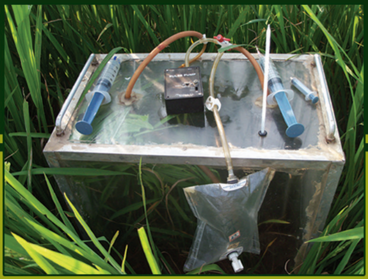
Ziska, L.H., Ziska, O.S., Namuco, T., Moya, & Quilang, J. (1997). Growth and yield responses of field-grown tropical rice to increasing carbon dioxide and air temperature. *Agronomy Journal,* 89, 45-53.

*****

Central Rice Research Institute
(Indian Council of Agricultural Research)
Cuttack 753 006, Odisha, India

Phone: 91-671-2367768/783 | Fax: 91-671-2367663
E-mail: crrictc@nic.in | directorcrri@sify.com

URL: http://www.crri.nic.in



ISBN 81-88409-12-X