Nutrient management and water use efficiency for sustainable production of rain-fed crops in the World's dry areas

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Chapter 7

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Abstract

Insufficient and highly variable precipitation, and frequently low soil fertility are the major biophysical constraints to agricultural productivity in farming systems in the dry areas which account for about 40% of the earth's surface land area. Such constraints can be mitigated by management interventions. Reduced runoff and evaporation can lead to increased crop yields in semiarid zones where land has been shaped into basins to retain rainwater on the field. Other practices that enhance rain-fed crop production include residual moisture after harvesting the main crop, local practices to increase the storage of rainwater or snow water; addition of manure and maintenance of crop residues to improve soil structure, to increase water infiltration into the rooting zone of crops and minimize evaporation losses; reduced tillage to conserve water; and improved fertilizer management, based on soil tests, and appropriate rates, timing and placement of nutrients. Soil fertility in intensified farming in the semiarid zones can be maintained only through the use of chemical fertilizers combined with the efficient recycling of organic materials, such as crop residues and farm manure, and the adoption of rotations with legumes, pulse crops, and green manures that fix nitrogen and improve soil quality. Thus, an understanding of interaction effects between soil water and nutrients is crucial for sustainable crop management in semiarid environments. The goal of optimized management is to attain the highest use efficiency of water as well as of nutrients. Using examples from developing and developed regions of the world, this chapter outlines the various factors underpinning efforts to improve crop production in dry areas through improved technologies and highlights constraints associated with adoption of such technologies by farmers.

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Introduction

Dry areas account for about 40% of the earth's surface land area (Turner *et al.,* 2011). Whether arid or semiarid, these are fragile environmentally and are defined by the absence of rain or low rainfall, often with variable distribution. Low soil fertility is frequently a compounding constraint in dry lands. Much has been written about the significance of dry lands and their significance for society (Unger *et al.,* 1988; Rao and Ryan, 2004; Peterson *et al.,* 2006). How such dry regions are managed can have implications for society as a whole. Burgeoning world populations, especially in lesser-developed countries, have led to increased land use pressure around the globe, with implications for sustaining livelihoods and natural resources and maintenance of fragile, vulnerable and drought-stressed ecosystems (Godfray *et al.,* 2010). With a crisis looming in world food production, the challenge of enabling countries dominated by dry areas to sustain their populations is enormous (Borlaug, 2007). In arid areas, crop production is not possible without irrigation, while in semiarid regions where irrigation is generally not an option, crop yields are dictated by low and erratic rainfall, typically with low yields and often complete crop failure. Variable rainfall limits the effectiveness of inputs such as fertilizers and increases the economic risk of fertilizer use.

Despite this dismal scenario, there is reason to believe that agriculture in arid and semiarid regions can, with improved management, be made more productive in a sustainable manner (Lal, 2001). Despite the crop production constraints associated with limited rainfall, crop yields in dry areas can be profitably increased and yield variation decreased with a combination of improved soil and crop management, such as using chemical fertilizers and adopting summer fallow, reduced tillage, and improved cultivars of drought-tolerant crops.

While dry regions of the world have many common features, in terms of the impact of such areas on society, one has to differentiate between dry areas in developed countries and those in developing countries. In developed countries, e.g. USA, Canada, and Australia, the scale of farming is vastly different from that in developing countries, due to the availability of resources, technologies and socioeconomic support structure. In contrast, dry-area developing countries are plagued by numerous constraints that limit responsiveness to drought. In short, how people cope with water shortages for agriculture depends on where in the world they live. Nevertheless, farmers in every dry region need a strategy that makes the most effective use of the limited rainfall, either to capture it more effectively, or reduce its evaporative loss. Thus, water availability is dependent on in-field conservation and effective crop use (Stewart *et al.,* 1993; van Duivenbooden *et al.,* 1999). Runoff, evaporation and deep percolation from the soil surface drastically reduce the proportion of rainfall available for plant growth. Additional water can be made available to crops from the local rainfall by following low-cost, low-risk land and water management strategies, often based on practices from antiquity; even small amounts of additional water can significantly increase yields in dry environments with high water use efficiencies - provided that factors that impinge on water use are adequately addressed. Crop choice can also be an important management tool.

Foremost among the factors affecting crop yields and water use efficiency (WUE) are essential plant nutrients, especially nitrogen (N), phosphorus (P) and, to a lesser extent, potassium (K), some secondary nutrients and micronutrients. Adequate nutrition of crops, especially involving chemical fertilizers, is as vital to food security in dry areas of the world as it is globally (Roy *et al.,* 2006). Historically, minimum required soil fertility for low-output agriculture was maintained by externally applied organic inputs. While resource-poor developing countries are still heavily dependent on organic manures to support crop yields, chemical fertilizer application is nowadays used for over 50% of the world's food production and is likely to gain further significance in the future (Stewart *et al.,* 2005). Manure supply in developing countries is generally determined by animal size and type, as well as by the requirement of manure for fuel. Increasing pressure to enhance crop production in water-limited areas will inevitably lead to increased fertilizer use integrated with available organic sources. Regardless of the source of nutrients for future crop production in such areas, nutrient use efficiency will be dictated by rainfall or soil moisture availability, and the efficiency of use of the limited water will be dependent on the availability of essential crop nutrients. In essence, this synergy or interaction between the two factors, water and nutrients, is at the core of crop management in dry areas (Henry *et al.,* 1986).

Traditionally, the development approach for arid and semiarid regions for crop production has focused on single elements of the farming system such as fertilizer use, soil management, or water conservation measures (Unger *et al.,* 1988; Peterson *et al.,* 2006). Substantial impact on crop yields has often failed to emerge following this fragmented approach. Successful strategies to increase dryland crop output is likely to involve an integrated approach involving soil and water conservation measures and nutrient inputs (Rao and Ryan, 2004; Roy *et al.,* 2006). Thus, this brief and general review examines the relationship between water and nutrients in dryland crop production, highlighting technologies for more effective water capture in the farmers' fields and approaches to enhance its use by the crop.

Comprehensive reviews of dry area agriculture are found in Peterson *et al.* (2006) and in a tome just published that gave a global perspective (Tow *et al.,* 2011). In the past, because of the dramatic yield increases that can be produced by irrigation, that sector has had disproportionate research attention. Conversely, semiarid regions that are dependent on low seasonal rain to produce crops have received less research attention and funding for development, notwithstanding calls to the contrary (Lal, 2001). In view of the growing significance of rain-fed or dryland agriculture, focus in this selective review is on agriculture sustained by natural rainfall and to consider soil fertility management and water productivity from its capture in the field to its use by the growing crop. This chapter describes location-specific and integrated soil, water and nutrient management strategies that can lead to sustainable farming systems in arid and semiarid environments using examples from around the world, including developed and developing countries.

Arid and semiarid environments

Definition, characteristics and global distribution

Arid environments are defined as those in which the amount of precipitation received divided by the amount lost to evapotranspiration yields a fraction between 0.03 and 0.20; the corresponding fraction for semiarid regions lies between 0.20 and 0.50 (FAO/UNESCO/WMO, 1977). Though very diverse in terms of landforms, soils, water balance and fauna, these environments are characterized by low annual precipitation (0 to 800 mm), which occurs infrequently and irregularly. The arid zones are characterized by no cultivation, except sparse grazing, due to the very low rainfall (generally below 200 mm yr^{-1}); under such conditions, cropping is possible only with irrigation. The semiarid zones can support rain-fed agriculture with more or less sustained levels of production (Peterson *et al*., 2006). Based on the length of the growing period for annual crops, arid regions have 1-59 growing days whereas in semiarid regions the number of growing days is between 60 and 119 (FAO, 2000).

Dry or moisture-deficient lands occur in most continents. Africa accounts for about one-third of the world's dry areas (Tow *et al.,* 2011), which also occur in Central Asia, the Middle East (including West Asia and North Africa (WANA)), Australia, as well as North, Central and South America. In Asia, semiarid lands also occur in Russia, China, Mongolia and the Indian Subcontinent. About 75% of Australia is arid or semiarid. In South America, semiarid lands are mainly located in Argentina. Semiarid lands of North America extend from Mexico to Canada, the Great Plains, the Pacific Northwest region, and the Southwest Pacific region of California (UNEP, 1992). Based on differences in temperature, the season in which rain falls, windiness and in the degree of aridity, arid and semiarid environments are found in three major climate types: the Mediterranean climate, the tropical climate and the continental climate. In the Mediterranean climate, the rainy season is during autumn and winter. Summers are hot with no rains and winter temperatures are mild (Kassam, 1981). Major dryland-farming areas with a Mediterranean-type climate are in southern Europe, across North Africa, West Asia extending into Central Asia, Chile, Australia, and parts of California and the US Pacific northwest extending to British Columbia and Canada (Peterson *et al.,* 2006). Under tropical conditions, rainfall occurs during summer; the rainy season decreases with distance from the equator. Winters are long and dry. Arid and semiarid areas within the tropics cover most parts of the developing nations in the world, including Latin America, large areas of West, Central, eastern and southern Africa and parts of India and South-East Asia. In the continental climate, precipitation is distributed evenly throughout the year, although there is a tendency toward greater summer precipitation. Continental climate is found in parts of Australia, Russia, Central Asia and the North American Great Plains.

The semiarid regions of Northern Great Plains of the USA and Canada differ from agricultural production systems from the rest of the world insofar as generally low input production systems are combined with highly mechanized large-scale farm areas (Peterson *et al.,* 2006). The continental climate prevalent in the region is characterized by short, dry, hot summers and long, cold winters. About half of the annual precipitation occurs between May and September, and about one-third comes as snow in winter. Snow is a potentially important source of available water and it insulates and protects the soil from erosion; Swift Current (Saskatchewan, Canada), is typical of such conditions.

Constraints to crop production

Crop production in dry areas is constrained by the highly erratic and low rainfall, high temperature, winds, low atmospheric humidity regimes and the degradation of soils due to erosion, low soil organic matter (SOM) content and deficiency of plant nutrients. Much of the rainfall in these environments is eventually returned to the atmosphere by evapotranspiration, especially in tropical regions where rainwater falls on hot soil surface in summer, resulting in rapid loss of soil moisture due to the high levels of evaporation and transpiration. Evaporation increases with strong winds, high temperatures, and low humidity. The SOM content of dry-area soils, which influences fertility and soil physical properties, especially water-holding capacity, is generally low, and rapidly declines when such soils are cultivated. The production of crops in dry water-stressed regions is influenced by the extent to which the limited rainfall is held in the field and not lost from being used by the crop, as well as the efficiency with which the growing crop uses the limited amount of moisture (Koohafkan and Stewart, 2008). Thus, it is pertinent to briefly describe the practices used for rainwater capture in the dry-area landscapes and on farmers' fields prior to considering the efficiency of crop water use. Some in-country examples are illustrated.

Rainwater collection and conservation

As crop yields tend to increase with increases in transpiration, effective rain-fed farming systems should reduce runoff and evaporation from the soil surface in order to increase efficiency of water use, i.e. a higher proportion of precipitation must be used for transpiration. Thus, the emphasis in farming in dry regions is on capturing, storing and utilizing highly variable and scarce precipitation, and on minimizing loss to runoff and evaporation. This can be achieved by two management strategies as described by Koohafkan and Stewart (2008): (i) *in situ* water conservation (e.g. summer-fallowing and snow trapping in Canadian prairies); and (ii) water harvesting. Preventing runoff, keeping as much rainfall as possible where it falls and minimizing evaporation, lead to *in situ* water conservation. Water harvesting is the collection of rainwater and runoff and its later productive use for growing crops.

In situ water conservation

Several technical interventions have been developed and shown to be effective in dry-area regions to enhance *in situ* conservation of rainwater. The success of technical interventions often depends on location-specific biophysical and socioeconomic conditions, and often requires local community action.

Terraces

Terraces have been used for centuries to control runoff and erosion; their design and construction are guided by local conditions because of landscape diversity. Bench terraces, the oldest type of terraces, are constructed with soil from the uphill side of a strip being brought to the lower side so that a level step or bench is formed (Figure 1). Radiocarbon dating indicates that the bench terraces in the Colca Valley in Peru were built at least 1,500 years ago (Sandor and Eash, 1995). One of the most extensively terraced areas in the world exists in Yemen (Koohafkan and Stewart, 2008). Dryland farming has occurred on these terraces over the past three millennia, and much indigenous agricultural knowledge of these terraces survives even today. Terracing is still relevant today; for instance, in China, more than 2.7 million ha of cropland were terraced from 1950 to 1984.

Conservation bench terraces

Conservation bench terraces (CBTs), or Zingg terraces, use a part of the land surface as a catchment to provide additional runoff onto level terraces where crops are grown (Figure 1). These are particularly suitable for large-scale mechanized farming such as the wheat/sorghum farmlands of the southwestern USA. In comparison to conventional level terraces, CBTs effectively control erosion and reduce overall runoff, and reliably increase yields where rainfall is sufficient (i.e., 300-600 mm) for reasonable crop production (Koohafkan and Stewart, 2008). For most effective operation, the design of CBTs should be location-specific. Due to large installation costs, conservation terraces are probably not viable in very low rainfall areas (<300 mm).

Contour furrow

Contour furrows, or desert strip farming, are similar in principle to that of CBTs, but require less soil movement. This is why they are more popular with small farmers and/or in lower rainfall areas. Furrows or ridges follow the contour at a spacing of usually 1 to 2 meters (Figure 1). With the catchment area left fallow, cropping is usually intermittent on strips or in rows. If the contour furrows are not laid out precisely on the contours, uneven ponding depth behind the bank can occur, but it can be reduced by making small bunds at right angles (FAO, 1987). Sometimes the excavated furrow is made to collect water so that in exceptional storms the runoff can overflow without damage.

Contour bunds

Contour bunds are built on a level grade with ties in the basin. A stone wall is built on the lower side of the earth bund so as to reduce damage in case the basin is overtopped (Figure 1). Using contour bunds in Kenya, sorghum was grown with only 270 mm of rainfall with a catchment ratio of 2:1. Runoff from the catchment was 30%, giving 162 mm of runoff, and 432 mm available to the plants (Smith and Critchley, 1983). In Ethiopia too, contour bunds are being used for soil and water conservation.

Laser-assisted land leveling and mini benches

Laser-assisted land leveling and mini benches and leveling with laser is expensive but it is most effective in reducing runoff losses. For example, in the Tadla region of

Morocco there were substantial benefits from this approach, i.e. 20% water savings, 30% increase in crop yields, and 50% labor savings, while achieving 90% of irrigation uniformity (Koohafkan and Stewart, 2008). An alternative to land leveling is the use of narrow mini-benches which can be constructed economically on gentle slopes, i.e. up to 2% (Jones *et al.*, 1985). Since soil cuts are relatively shallow in mini-benches, soil-fertility problems associated with the redistribution of large volumes of surface soil are considerably reduced. As mini-benches do not require much soil to be moved, these are less expensive to construct.

Tied ridges

Furrow-diking or tied-ridges are proven soil- and water-conservation methods under both mechanized and labor-intensive farming systems. These involve growing crops on small ridges on the contour while blocking the furrows with cross-ties or dykes to retain rainwater for infiltration (Figure 1). Crops can be grown on the contours under all types of tillage, including reduced-tillage and no-tillage systems. However, tied ridging has not been widely adopted by small farmers, mainly because of inconsistent benefits. Both soil texture and rainfall regime need to be considered when evaluating tied ridges. In

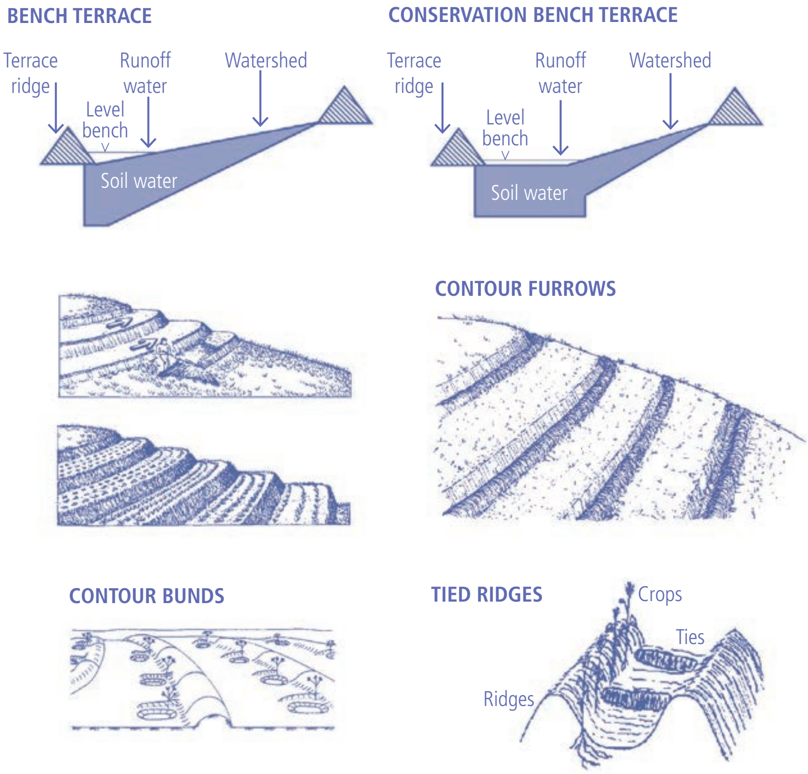

Figure 1. Different *in situ* water conservation systems followed in dry-area regions of the world.

East Africa, tied-ridges were successful at near normal rainfall (i.e. 500-600 mm), but mostly counterproductive above 700-900 mm due to anaerobic conditions in the root zone and nutrient leaching (Jensen *et al.,* 2003).

Surface mulching

Stubble mulch, no-till, and snow management techniques are commonly used in North America. Tillage systems that leave crop residues on the soil surface are essential to control wind and water erosion in most areas of the Great Plains. Conservation tillage also increases soil water storage during fallow periods (De Jong *et al.,* 2008), which increased crop yields and facilitated the more efficient use of other improved technologies, especially fertilizers and improved cultivars. However, selecting appropriate water conservation strategies requires careful consideration of local conditions. Some technologies may not show positive results for one or more succeeding years. Success of *in situ* water conservation practices depends on leaving crop residues on the soil surface as a mulch to conserve water and enhance SOM. While cultivation across the slope was the only conservation practice used by most Indian farmers (Kerr *et al.,* 2002), they recognized the value of mulches and retaining stubble in the dry season, but they did not follow the practice because cut stubble was needed for fuel and feed.

The following strategies, based on amount of rainfall and water requirement of the crop have been suggested by Dhruva and Babu (1985): (a) when precipitation is less than crop requirements – increase runoff onto cropped areas, increase fallowing for water conservation, and grow drought-tolerant crops; (b) when precipitation is equal to crop requirements – increase local conservation of precipitation, thus maximizing storage within the soil profile, and increase storage of excess runoff for subsequent use; and (c) when precipitation is in excess of crop requirements – reduce rainfall erosion, by draining surplus runoff and storing it for subsequent use. Wide seasonal variation in rainfall/moisture makes the choice of strategy difficult as it is not practical to classify methods according to average conditions, or to design strategies based on averages; dual purpose strategies including methods that can be changed in mid-season may be preferable, (e.g. opening up the ends of contour bunds to shed surplus water after a wet start to the season, or to block outlets for the opposite effect), but only a few methods allow this flexibility.

Water harvesting

Water harvesting consists of collecting rainfall from a modified or treated area to maximize runoff for use on a cultivated field, or for storage in a reservoir, or for aquifer recharge; rainfall should, as far as possible, be harvested where it falls. In general, three types of water-harvesting techniques are followed: (i) microcatchments; (ii) macro-catchments; and (iii) floodwater harvesting.

(i) Micro-catchment systems, consisting of a catchment area and an adjacent cultivated area, are simple, inexpensive and easily reproducible, and offer significant increased cropping potential to smallholders in developing countries. Natural depressions, contour bunds, interrow water harvesting, semicircular and triangular bunds can act as micro-catchments, depending on the local conditions. In areas of Jordan with rainfall less than 150 mm yr^{-1}, water harvested and stored in small-basin micro-catchments resulted in an overall system efficiency increase by 86% (Oweis, 1997). In Hamadan, Iran, rainwater is collected from sloping surfaces into channels running along slope-breaks and distributed to parcels of land located below the slope-breaks. Some of these techniques are the product of local people's ability to manage scarce water resources on a sustainable basis (Farshad and Zinck, 1998). In Burkina Faso, micro-catchments established as runoff-farming techniques increased agricultural production due to increased infiltration by constructing simple contour bunds.

(ii) Macro-catchments collect runoff from a large area located at a significant distance from the cultivated area. External catchments include hillside-sheet or rill-runoff utilization, and hillside-conduit systems.

(iii) Floodwater harvesting within a stream-bed involves blocking the water flow, causing water to concentrate in the stream-bed which is then cultivated. It is important to make sure that the stream-bed area is flat with runoff-producing slopes on the adjacent hillsides, and that the flood and growing seasons do not coincide. Water in an ephemeral stream can also be diverted and applied to the cropped area using a series of weirs, channels, dams and bunds.

Reducing evaporation

Evaporation, during both the fallow period and the crop growing season, is a major cause of water loss. Surface mulching with crop residues and plastic films modifies the hydrothermal regime of the soil by influencing the radiation balance, rate of heat and water vapor transfer and heat capacity of the soil. Mulches left on the soil surface or dust mulch created by repeated plowing (common in South Asia) have proved effective in reducing evaporation during fallow periods. While stubble-mulch techniques are commonly used on the North American Great Plains and minimum tillage and no-tillage are steadily increasing (Zentner *et al.,* 2002), dust mulch is not used anymore because of erosion concerns. Heavier mulch coupled with no-tillage can present a problem of wet soil at seeding. Organic mulches improve rainfall acceptance, and reduce runoff and surface crusting. In the North China Plain and Loess Plateau, mulching with crop residues can improve WUE by 10-20% through reduced soil evaporation and increased plant transpiration (Deng *et al.,* 2004). Wheat stubble was about twice as effective in decreasing soil water evaporation as grain sorghum stubble and more than four times as effective as cotton stalks (Unger and Parker, 1976). In the semiarid tropics in India, maize yields increased 16% and sorghum 59% with rice straw mulching (Cogle *et al.,* 1997). When several precipitation events occur over a period of a few days, the residues left on the soil surface as mulch are the most beneficial for reducing evaporation because each successive precipitation event leads to soil wetting to a greater depth. Reducing evaporation during the growing season is more challenging. For example, sorghum responded more to the amount of soil water at the time of seeding than to the presence of mulch during the growing season (Unger and Jones, 1981).

Possibly, shading from the plant canopy largely substituted for the beneficial effect of mulch during the growing season.

Enhancing water use efficiency

Water use efficiency, a key element in rain-fed crop production in dry areas, is defined as the amount of harvestable product produced per unit of evapotranspiration from crop seeding to harvesting. Biomass production, grain yield, and evapotranspiration dictate efficiency. With wheat cropping at two semiarid locations, Texas in USA and Shaanxi in China (Stewart *et al.,* 1993), evapotranspiration was about 65% of total precipitation. Water available for plants decreased during the growing season and increased during the fallow period but the change was considerably less for Texas than for Shaanxi as the former had less precipitation during the fallow period and a very high potential evapotranspiration. While total precipitation was greater at Texas than at Shaanxi, actual evapotranspiration during the wheat-growing season was also greater at Texas. According to Hatfield *et al.* (2001), overall, precipitation use efficiency in semiarid environments can be enhanced through adoption of more intensive cropping systems. Efficient nutrient management practices can further increase WUE.

Dryland nutrient-water interactions

While water availability in dry areas can be increased through various practices discussed above, adequate water alone cannot ensure higher crop yields. Adequate plant-available nutrient supply is also essential to maximize the benefits of additional water captured or saved. This is especially true for N (Ryan *et al.*, 2009). Thus, it is pertinent to briefly consider how soil water influences the dynamics of N and vice versa. Rainfall and its variable distribution influence various soil biological and chemical processes. Water pulses may directly affect the frequency and duration of wet-dry cycles in the soil and, therefore, different aspects of carbon and nutrient turnover, including C and N mineralization, microbial biomass, gaseous losses, denitrification and ammonia volatilization (Austin *et al.*, 2004). One consequence of the frequently observed flush of N mineralization in surface soil layers after wetting and drying events associated with the bimodal rainfall season is the accumulation of inorganic N. But due to occurrence of maximum water and soil N concentrations at different moments during the year, there exists asynchrony of N and water availability resulting in low N availability to crop plants in arid and semiarid ecosystems. Therefore, an understanding of interaction effects of soil water and nutrients is crucial for developing management strategies for achieving high yields and use efficiency of both water and nutrients in water-stressed regions.

Nutrient management for enhancing water use efficiency

Positive impact of fertilizers in nutrient-deficient soils in relation to WUE has been demonstrated by various researchers cited in proceedings of many international conferences (Monteith and Webb, 1981; van Duivenbooden *et al.,* 1999; Rao and Ryan, 2004; IAEA, 2005). Fertilizer not only enhances plant growth but also stimulates root growth to allow water uptake from deeper soil layers, particularly during drought spells. The rapid growth of plant canopy due to fertilizer application provides shade on the soil surface and, thus, reduces the proportion of water that is evaporated. However, if such early growth is followed by a dry period, die-off of early cereal tillers and reduced heading occurs (Campbell *et al.,* 1977 a, b). In a rain-fed maize-wheat rotation in a semiarid region of northern India, application of 80 kg N ha^{-1} to wheat resulted in greater water utilization from a 90-180 cm soil layer compared with unfertilized crop (Singh *et al.,* 1975). At Fuxing in China, the magnitude of production factors on maize yield was in the order of N >water >P (Sun *et al.,* 2009); synergistic effects were in the order N and water > P and water > N and P. In another study (Kathju *et al.,* 2001), it was found that application of 80 kg N ha^{-1} significantly increased WUE by local hybrids and composite varieties of pearl millet.

At several field locations in China, N application increased WUE by about 20% (Deng *et al.,* 2004). In multilocation water-balance studies in Niger, fertilizer application increased WUE regardless of seasonal rainfall (Table 1). In another experiment with pearl millet, fertilizer use increased seasonal crop-water use modestly (i.e. 5.4-14.4 kg mm^{-1} ha^{-1}) due to substantial increase of crop growth and yield (Bationo *et al*., 1998). Phosphorus fertilization may also enhance WUE by improving growth and development of plant foliage and roots. For example, P application in soils of variable texture in different rain-fed regions of India increased WUE by 15-20% in dryland wheat, 22-55% in finger millet, 41-99% in chickpea, 17% in linseed and up to 19% in a mixed wheat-chickpea cropping system (Tandon, 1987).

Table 1. Effect of fertilizer (NPK) application on water use efficiency and grain yield of pearl millet grown at four sites in Niger during rainy seasons of 1985 and 1986 (adapted from ICRISAT, 1985).

	Sadoré (rainfall 543 mm)		Dosso (rainfall 583 mm)		Bengou (rainfall 711 mm)	
	Yield (t ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Yield (t ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})	Yield (t ha^{-1})	Water use efficiency (kg ha^{-1} mm^{-1})
Fertilizer	1.57	4.14	1.70	4.25	2.23	4.68
No fertilizer	0.46	1.24	0.78	2.04	1.44	3.08
S.E.	162	0.44	103	0.26	126	0.22

Water management for enhancing fertilizer use efficiency

Increased soil-water storage and availability to crop plants at critical growth stages improves utilization of fertilizer and other farm inputs (van Duivenbooden *et al.,* 1999). In India, higher yield of post-monsoonal sorghum was obtained in a deep soil having more stored water compared to a shallow soil, with response up to 50 kg N ha^{-1} in the deep soil and only up to 25 kg N ha^{-1} in the shallow soil (Singh and Das, 1995). In a sandy soil in southern Niger, mid-season (mid-July to end of August) rainfall determined the fertilizer N use efficiency (FNUE) and millet yield (Bationo *et al.,* 1989). With low mid-season rainfall, fertilizer N did not affect the millet yield; with average or above-average rainfall, N application increased millet grain yield fourfold to fivefold. A model relating yield of pearl millet to mid-season rainfall predicted limited responses to applied N in dry years, but higher responses in years of optimal rainfall, when fertilizer N application at 30 kg N ha^{-1} resulted in an FNUE as high as 25 kg grain kg^{-1} N (Bationo *et al.,* 1989).

In experiments on maize for 16 years in north-eastern China (Ma *et al.,* 2010), the highest yields occurred in normal rainfall years; responses of both P over N, and of K over NP occurred only in normal rainfall years (Table 2). Significant responses of either P or K were not observed under drought or in high rainfall years. The lowest yields occurred in years of drought or waterlogging, i.e. 44.7-58.5% of normal-year yields. In India, response of rainy season sorghum to applied N varied from 6.5 kg grain kg^{-1} N at Bellary (total seasonal rainfall 500 mm), 9.7 kg grain kg^{-1} N at Bijapur (680 mm), 19.0 kg grain kg^{-1} N at Solapur (722 mm) and 27.7 kg grain kg^{-1} N at Kovilpatti (700 mm) (Rao and Das, 1982). In addition to total seasonal rainfall, rainfall distribution during the crop growth period also affects FNUE. With a long-term rotation experiment at Swift Current, Saskatchewan, Canada, the grain-filling period was found to be the most important for both fallow- and stubble-seeded wheat, but precipitation at or near seeding time was almost as important for stubble-seeded wheat since this ensures the establishment of an adequate plant density (Campbell *et al.,* 1988). In northern India, the amount and distribution of rainfall during vegetative and reproductive phases of rain-fed wheat determined FNUE (Sandhu *et al.,* 1992). The rainfall pattern may also modify the effectiveness of the fertilizer application method. For example, in India (Singh *et al.,* 1977), the benefit of fertilizer N placed below the seed over broadcast application was less with rainfall occurring soon after planting wheat compared to when rain was delayed. In the semiarid Canadian prairies (Campbell *et al.,* 1993), water use was shown to be the most important factor influencing yield of spring wheat, accounting for 64% of the variability, and soil test N the second most important factor, accounting for 20% of the variability.

Table 2. Grain yield of maize (t ha^{-1}) with N, NP and NPK fertilizer application* under different precipitation years in a long-term experiment at Shilihe, Shenyang, northeastern China (adapted from Ma *et al.*, 2010).

Precipitation	N	NP	NPK
Drought (<400 mm)	3.60Aa**	4.19Ab	4.27Ab
Normal (400-550 mm)	6.78Ca	7.59Cb	8.43Cc
High (550-650 mm)	5.74Ba	6.56Ba	7.56Bb
Waterlogging (>650 mm)	3.03Aa	4.64Ab	5.41Ab

* Fertilizer application levels were 150 kg N ha^{-1}, 17.9 to 25 kg P ha^{-1}, and 60 kg K ha^{-1}.
** The same small letter in a row indicates that figures are not significantly different with different fertilization levels, and the same capital letter in a column indicates that figures are not significantly different with different precipitation years according to Fisher's Protected LSD test at the 5% level of probability.

Nutrient management options under rain-fed conditions

Given the known interactions between water and nutrients, it is pertinent to exploit such relationships in order to sustain or increase crop yields in water-stressed environments. In the following section, examples are given of water-nutrient management options in a number of dry regions in the developing world, e.g. Mediterranean region, Africa, India and China while the developed world is represented by Canada.

Mediterranean and west Asia-north Africa regions

In the past few decades, significant developments have occurred in the Mediterranean and west Asia-north Africa regions (WANA) region to increase agricultural output by introducing high-yielding crop varieties, mechanization, pest control, and particularly the use of chemical fertilizers as a supplement to the limited amount of animal manures available (Ryan *et al.*, 2012). As a country which is mainly arid desert and steppe land, Syria has a sizeable area in the semiarid zone (annual rainfall 250-500 mm) where dryland agriculture is practiced, primarily involving cereals, barley in the drier areas and wheat in the more favorable areas, as well as feed and food legumes (Cooper *et al.*, 1987); the grazing animals are an integral part of the cropping system where dryland agriculture has been practiced in the region for millennia. As the range of rainfall and other environmental conditions in Syria are generally similar to the conditions prevailing throughout much of the WANA region, the dryland research that emanated from Syria is applicable to most of the Mediterranean region (Monteith and Webb, 1981). Historically, without fertilizers, legumes were important in maintaining soil fertility, along with fallow to conserve moisture in the alternative year. In view of declining fallow due to land-use pressure, and other cropping system developments, several long-term rotation trials sought to provide viable economic alternatives for farmers. Subsequently, the significance of crop rotations in the farming systems were reviewed by Ryan et al. (2008a), highlighting the role of rainfall and nutrients.

In the WANA region, there was a direct relationship between rainfall and soil moisture and N response, with generally little difference between fall and spring N application; however, top-dressing in spring allowed more flexibility in relation to rainfall (Ryan e*t al.,* 2009). Crop responses to N were the highest where rainfall was favorable (350-500 mm) and minimal when rainfall was below 250 mm, and these were conditioned by the level of SOM, which in turn was related to the particular crop rotation (Ryan *et al.*, 2010). While urea is the dominant N fertilizer, it is prone to high volatilization losses. However, if mixed into the soil or applied under cooler conditions, or top-dressed just before or during spring rains, the loss is minimal (Abdel Monem *et al.,* 2010). Under dryland conditions, N losses from leaching were minimal. Studies on WUE considered crop yields in both phases of the rotation. The wheat-lentil and wheat-vetch systems were most efficient at using rainfall, producing 27% more grain than the wheat-fallow system (Pala *et al.*, 2007).

The influence of rainfall on crop yields across the rainfall gradient in northwest Syria was influenced by N besides other factors. Crop responses to P were observed in the fields where soil test levels for P were low – in areas where P buildup was observed due to regular fertilization, there was little or no response to P application (Ryan *et al.,* 2008b). Responses to P tend to be higher under drier conditions due to a stimulating effect on root growth (Pala *et al.,* 1996). Responses of dryland crops to N and P fertilization will be limited, unless micronutrient deficiencies (such as zinc, iron, boron) or toxicities (such as that of boron) are taken care of (Rashid and Ryan, 2008). As a consequence, measures were taken to promote the use of micronutrient fertilizers, while simultaneously breeding for boron tolerance.

Given the demonstrated essentiality of adequate nutrients for economic production of rain-fed crops in the WANA region, a collaborative soil test calibration program established guidelines for fertilizer application for the main crops (Ryan, 2008a). Particular emphasis was given to balanced fertilization (Ryan, 2008b). Due to continuously increasing cost of fertilizers, efficiency of nutrient use is going to assume further importance in the years to come. This can be achieved by considering various site-specific factors (i.e. rainfall, soil texture, SOM level, soil tests for different nutrients, the crop, method of tillage) that affect efficient nutrient use (Ryan *et al.,* 2010). Conservation- or minimum-tillage requires modifications in fertilizer application methods.

Arid and semiarid Africa

Increased gaseous losses of N from applied fertilizer with increasing rates of application, and regardless of N sources, have been reported in the dry regions of Africa (Bekunda *et al.,* 1997). Calcium ammonium nitrate (CAN) significantly outperformed urea in plant N uptake, which was translated into significantly higher yields of pearl millet (Mughogho *et al.,* 1986). Total N uptake by plants, however, was low (20 to 37%), and losses were high (25 to 53%). In field studies on millet in West Africa (Christianson and Vlek, 1991), crop N uptake was three times higher from point-placed CAN than from point-placed urea; also, crop N uptake was 57% less from broadcast CAN compared to point-placed CAN. Split-application of N increased NUE (Uyovbisere and Lombin, 1991). In southern Niger, responses to applied fertilizer N were improved by split-application as well as by tilling the soil, and with placement in the soil rather than leaving at the soil surface.

Cereal grain production on semiarid soils is more sustainable when mineral and organic fertilizers are combined (Palm *et al.,* 1997). In Sudan, sustainable sorghum production was ensured only when mineral fertilizers were combined with manure (Sedogo, 1993). There is ample evidence pertaining to widely different soil types and climates that organic inputs from crop residues, livestock manure and green manures can enhance fertilizer efficiency as well as crop yields (Palm e*t al.,* 1997; Place *et al.,* 2003). Some legume species not only fix N biologically at minimum cost, but also improve P availability, and thus increase crop yields (Snapp and Silim, 2002). Grain yield profitability increased by 50% or more when fertilizer was applied to maize after a grain legume in rotation, or a maize-legume intercrop, compared to continuous maize (Waddington and Karigwindi, 2001). Nevertheless, there are considerable constraints to the adoption of legumes for green manuring by farmers, primarily the high labor requirements and lack of access to seed.

Effective conservation of water can enhance beneficial effects of fertilizer application. Sorghum grain yields at on-farm locations in Burkina Faso were higher with the combination of fertilizer and tied ridges than with either fertilizer or tied ridges alone (Nagy *et al.,* 1990). In Zimbabwe, sorghum yields increased from 118 to 388 kg ha^{-1} by planting the crop on 1.5 m tied ridges, and to 1,071 kg ha^{-1} when 50 kg N ha^{-1} were applied to the tied-ridges during a low rainfall season (Nyakatawa, 1996). Nitrogen use efficiency is also influenced by the cropping system; for example, in West Africa, mean grain yields for 4 years were lower for continuous cropping of pearl millet supplied with 45 kg N ha^{-1} than for millet-cowpea and millet-groundnut rotations (Bationo *et al.,* 1998). Similar observations have been reported for the maize-cowpea rotation in Zimbabwe (Mukurumbira, 1985). In Malawi, average grain yield of maize (with no fertilizer N application), following pigeon pea, was on average 2.8 t ha^{-1} higher than that of maize following maize with an application of 35 kg N ha^{-1} yr^{-1} (MacColl, 1989).

In the context of N fertilization, evidence suggests that crop yields declined over time when only mineral fertilizer was applied (Bekunda *et al.,* 1997). This was likely due to: (i) *mining of nutrients* as higher grain and straw (if not recycled in the soils) yields remove more nutrients from the field than added (Scaife, 1971), (ii) *increased loss of nutrients* through volatilization and denitrification, and (iii) *SOM decline*. In Burkina Faso, fertilizer N application to monocropped sorghum (residues removed from the field) accelerated the annual rate of SOM loss from 1.5% without fertilizer, to 1.9% with moderate rates of N fertilizer, and 2.6% with high N rates (Pieri, 1995).

There is a fundamental disconnection between available fertilizer management options and resources and problems faced by the farmers in regions of dry areas of Africa. It appears wiser to suggest incremental and flexible recommendations that take into account the available resources and expected cost-effectiveness, rather than focusing on blanket package recommendations that may maximize the yields only (Okali *et al.,* 1994). Whereas fertilizer use research has been focused on examining rather minor variations in types and generally high rates of costly fertilizers, the average fertilizer use by farmers of sub-Saharan Africa remains stagnant at around 10 kg ha^{-1}. Though the arguments for enhancing fertilizer use in Africa are compelling, this cannot happen unless the constraints (such as lack of resources and knowledge) faced by smallholder farmers are addressed (Snapp *et al.,* 2003). The highly unpredictable environment in the semiarid tropics increases the economic risk on the investment in fertilizer, because there is no possibility of crop productivity increases with N fertilizer during the years with low rainfall (Snapp *et al.,* 2003). This risk can be minimized by adopting a 'response farming' technique that uses early rainfall events to decide on the N fertilizer rates for the approaching season, i.e. by adjusting split fertilizer applications to the expected rainfall events (Piha, 1993). Further, yield increases may occur when fertilizer practices are combined with soil moisture conservation practices, e.g. by planting the crop on tied-ridges. 'Response farming' increased maize yields in Zimbabwe by 25-42% and thus resulted in 21-41% more profit than did the existing fertilizer recommendation practice (Piha, 1993). In favorable rainfall years, the profits of participating farmers were 105% higher than those of a control group of comparably good farmers in the area.

In addition to N, the role of P is vital to crop production, particularly in acid soils in West Africa, and it revolves around the quest for more suitable and economic alternatives to conventional fertilizers. Direct application of powdered reactive (P-containing) rocks, as an alternative to soluble P fertilizers, has been observed to correct P deficiency in acid soils, as well as to leave a beneficial residual effect (Gerner and Mokwunye, 1995). Amongst the P rocks tested, Tilemsi and Tahoua were potentially viable alternatives to soluble imported P fertilizers (Bationo *et al.,* 1997). Partial acidulation of the low-reactivity phosphate rocks improved their performance (Buresh *et al.,* 1997).

In addition to technical improvements in N and P use practices, it is probably more important to implement the policies for guaranteed fertilizer availability as well as the credit line at affordable costs, and ensuring stable market conditions and reasonable product prices to justify investment into fertilizer.

Dry regions of India

Most extension services in India provide a single, standard fertilizer recommendation for large regions. Farmers have a few valid guidelines for adjusting N-fertilizer rates to account for the large differences in indigenous N supply, and thus have adopted the general recommendation. For example, about 90% of farmers in Hoshiarpur (Punjab state) have switched over to application of 40 kg N ha^{-1} for maize. In Alfisols of Telangana (Andhra Pradesh state), farmers are now using N and P fertilizers to grow sorghum and castor. Application of 40 kg N ha^{-1} and 13 kg P ha^{-1} to sorghum increased the average grain yield to 2,300 kg ha^{-1} or 2.5 times the yield from the farmers' fertilizer use practice. Similarly, 50 kg N ha^{-1} and 13 kg P ha^{-1} in castor resulted in a higher bean yield (i.e. 1,136 kg ha^{-1}) than suboptimal application of 10 kg N ha^{-1} and 13 kg P ha^{-1} (698 kg ha^{-1}) (Sharma *et al.,* 2007).

Multi-location, on-farm field experiments in India demonstrated the importance of balanced fertilization in increasing yield of rain-fed crops and improving N use efficiency (Table 3). Based on several balanced nutrient management experiments, agronomic efficiency of applied N was improved by applying P and K fertilizers, by 6.7 kg sorghum grain kg^{-1} N, 10.3 kg pearl millet grain kg^{-1} N and 19.5 kg maize grain kg^{-1} N. Nitrogen use efficiency improved from a deplorably low 6 to 20% in rain-fed pearl millet, maize and sorghum (Prasad, 2009). In a long-term fertilizer experiment on K-deficient red

Table 3. Effect of balanced application of fertilizer N, P and K on yield and agronomic efficiency of applied N in rain-fed crops in India (Prasad, 2009).

Crop	Yield (t ha^{-1})			Agronomic efficiency (kg grain kg^{-1} N)	
	Control	N	NPK	N	NPK
Pearl millet	1.05	1.24	1.65	4.7	15.0
Maize	1.67	2.45	3.24	19.5	39.0
Sorghum	1.27	1.48	1.75	5.3	12.0

soils of Bangalore, finger millet responded substantially to NK application compared to NP. Rather, long-term use of NP alone resulted in a gradual decrease in yield, and inclusion of K greatly improved grain yields as well as FNUE (Vasuki *et al.,* 2009). At Bawal in the semiarid region in northwestern India, pearl millet responded significantly to application of K up to 33 kg K ha^{-1} in a loamy sand soil testing 132 kg ha^{-1} ammonium acetate extractable K. (Yadav *et al.*, 2007).

The standard fertilizer recommendation to rain-fed crops in semiarid regions in India is to drill or place the basal application 5 to 10 cm deep in the root zone. In the rainy season, a portion of the N dose and all P and K are applied basally. During the dry season, when little or no rainfall is expected, full amounts of nutrients for the entire crop season are recommended to be applied basally. The yield gains by adopting the recommended fertilizer placement method can vary from 340 to 1,500 kg grain ha^{-1} (Venkateswarlu, 1987). To achieve high fertilizer N use efficiency and to avoid adverse effect of fertilizers during drought spells, split application is essential. Amount and timing of the fertilizer application have to match the rainfall distribution; 2-3 split applications are recommended depending on the crop growth period. Split application of fertilizer N along with drilling and band placement of P fertilizers lead to substantial increases in crop yield as well as nutrient use efficiency in rain-fed crops (Sharma *et al.,* 2007).

Integrated plant nutrient supply systems advocated in arid and semiarid regions of India, involve monitoring all pathways of flow of plant nutrients in agriculture. It involves judicious and integrated use of fertilizers, biofertilizers, organic manures (farmyard manure [FYM], compost, vermicompost, biogas slurry, and green manures), and growing of legumes in the cropping systems. Legumes, including twigs of N-fixing trees, are sometimes as effective as 40-80 kg urea N ha^{-1} and constitute an important component of the integrated plant nutrient supply system. Apparent recovery of N applied entirely through urea and that of conjunctive use of loppings and twigs of N fixing trees such *as Gliricidia maculata or Leuceana leucocephala* and urea in 1:1 ratio (equivalent to 40 and 80 kg Nha^{-1}) was similar (Sharma *et al.,* 2002). Application of 10 t FYM ha^{-1} (wet weight) along with recommended fertilizer rates stabilized the productivity of finger millet at about 3,400 kg ha^{-1} with a crop yield index of 0.66 compared to 0.36 when only chemical fertilizer was applied. Continuous application of chemical fertilizers resulted in a decline in finger millet grain yield from an average of 2,880 kg ha^{-1} during the initial 5 years of the study to 1,490 kg ha^{-1} by the 19^{th} year (Gajanan *et al*., 1999). In Vertisols, providing 50% of the recommended fertilizer dose through crop residues and the remaining 50% through *Leucaena leucocephala* lopping enhanced the sorghum yield by 87, 31 and 45%, respectively, compared to the application of 25 kg N ha^{-1} and 50 kg N ha^{-1} as fertilizer (AICRPDA, 1999).

In on-farm nutrient diagnostic studies during 2002-2004 in the semiarid zone of India spread over the states of Andhra Pradesh, Tamil Nadu, Karnataka, Madhya Pradesh, Rajasthan and Gujarat (Sahrawat *et al.,* 2010a), it was found that 73-95% of the fields were deficient in S, 70-100% in B, and 62-94% in Zn. The consequent on-farm field trials showed significant yield increases of maize, castor, groundnut, and mungbean with applications of S, B and Zn, especially when combined with applications of N and P. Deficiencies of certain micronutrients are widespread in the semiarid regions of India, potentially constraining the crop production potential. The results from long-term field experiments show that integrated use of soil and water conservation practices along with balanced plant nutrient management can sustain increased crop productivity (Sahrawat *et al.*, 2010b). Thus, exploiting the synergy between soil and water conservation practices and integrated nutrient management at the watershed level in the Indian semiarid tropics is vital to improve and sustain dryland farming (Wani *et al.,* 2003).

Arid and semiarid China

In China, fertilizer is the most costly input in crop production, and increased use of chemical fertilizer in dryland farming has already doubled the grain yields. Before the 1970s, FYM was the main source of applied nutrients. Fertilizer use is increasing but in a ratio of N to P higher than the recommended ratio of 1:0.3 for dryland crops (Tong *et al.,* 2003). Excessive use of N fertilizer, inadequate use of P and K fertilizers, and neglect of organic manures are common features of nutrient management in semiarid regions of China. Consequently, yield responses to fertilizers and agronomic and recovery efficiencies of applied nutrients are very low (Yu *et al.,* 2007). Ammonium bicarbonate has been used as a main source of N fertilizer, which leads to higher NH_3 volatilization losses and lower N use efficiency than using urea (Wang *et al.,* 2003). Most of the fertilizer-crop yield trials in China were of short duration and thus provided limited information. Multiyear field trials are needed for arriving at more effective nutrient management recommendations in relation to the prevalent rainfall regimes by using chemical fertilizers and organic manures, where available (Ma *et al.,* 2010). Grain legumes, green manures, and crop rotations ought to be a part of that strategy (Deng *et al.,* 2004). The key is to adopt fertility-enhancing rotations, such as a grain crop with a summer green manure crop, a grain-oilseed-legume rotation or grain-legume intercropping, grain-grass intercropping or wheat-potato intercropping, in order to fully utilize the crop- growth factors, such as light, heat and water, to achieve increases in yield efficiency and farmer incomes.

Northern great plains: USA and Canada

The Canadian semiarid prairies are Aridic Borolls and Typic Borolls, and constitute the most important agricultural region of the country. Prairie soils are young and inherently fertile. Thus, crops mainly require N and P fertilizer, in limited cases S, but rarely K. Historically, this region has been dominated by cereal production – especially hard red spring wheat in either monoculture or varying with summer fallow (leaving land bare to conserve water). Over the past 30 years, the cereal-growing area (i.e. wheat, oats, and barley) has remained fairly constant but there has been a steady decline in summer fallow area with replacement by pulses and oilseeds (Campbell *et al.,* 2002). The recent economic advantages of crop diversification, coupled with significant progress in crop breeding and improved management methods, have resulted in a steady increase in the production of oilseeds and pulses such as canola, dry pea and lentil (Zentner *et al.,* 2002). Low precipitation limits crop yields (mostly < 3.5 t ha^{-1}, and in many cases only

1.5 t ha^{-1}), thus requiring low fertilizer inputs. Producers are adopting more intensive crop management practices, such as moving from conventional stubble mulch tillage to minimum and zero tillage (Zentner *et al.*, 2007). Like in most semiarid regions, crop productivity in the northern Great Plains of the USA and Canada is typically limited by available soil water and N.

Producers in this region have been provided with new or alternative crop production options, such as minimum and zero tillage management, cutting stubble tall to trap snow, choices of new crop types, and use of extended and diversified crop rotations, many of which enhance overwinter storage of water and water availability, reduce crop evapotranspiration, reduce soil degradation, and increase grain yields (Cutforth and McConkey, 1997). Moreover, it has been shown that fertilizers used prudently, guided by soil tests, and placed properly in the soil at or near the place of seeding, will enhance crop production and grain quality by minimizing nutrient losses to the air or groundwater compared to the commonly used fallow-wheat system (Janzen *et al.*, 1999).

Numerous studies have been conducted to examine the influence of N and P on yield and grain quality, as well as on water and N use efficiencies in the semiarid prairies of North America. Results of an ongoing 44-year experiment, initiated in 1967, show that yield responses were higher after 1990 than before that, reflecting the impact of better precipitation in the case of P treatments and the effect of both precipitation and increased N in the case of N treatments (Campbell *et al.*, 2005). The influence of fertilizer on yield depends on available water and there is often a positive interaction between these two components. For example, Henry *et al.* (1986) illustrated that the relative importance of water and N varies depending on the degree of stress imposed by each factor (Figure 2). When these two factors are varied over any appreciable range, the contribution of the interaction factor is as large as, or larger than, the effects of the individual variables. Using water deficit analysis of the long-term experiment at Swift Current (1967-2005),

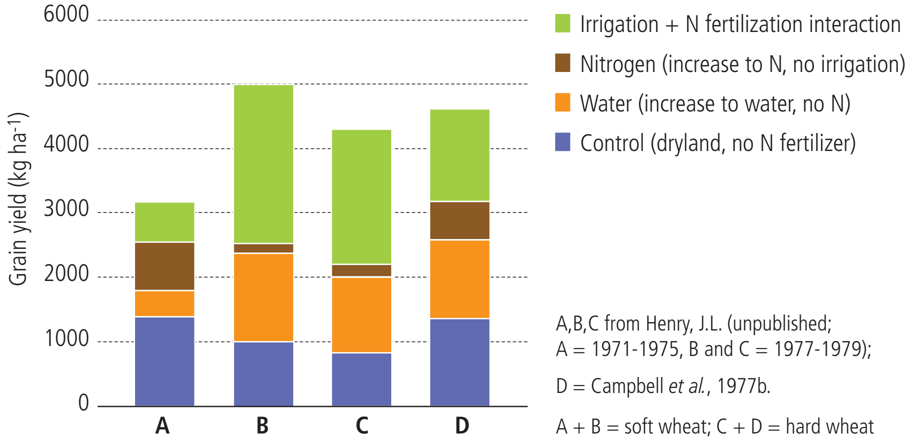

Figure 2. Effect of water, nitrogen fertilizer and their interaction on grain yield of wheat in Saskatchewan, Canada (adapted from Henry *et al.*, 1986).

WUEs in the rotation experiment were generally greater for treatments with N + P fertilizer, and greatest after an increase of N application coupled with favorable soil moisture conditions in the final decade of this study (Selles *et al.,* 2011). Under a semi-controlled mini-lysimeter experiment at Swift Current to assess the influence of water and N rate on stubble crop wheat yields (Campbell *et al.,* 1977 a, b), WUE increased more due to increasing water availability than due to increasing N rates. Scientists in this region of Canada have demonstrated that an even more sustainable management approach is to employ no-tillage management together with snow trapping to enhance overwinter soil water capture (Campbell, 1992) and reduce in-crop evapotranspiration (Cutforth *et al.,* 1997, 2002). It was shown that there may even be greater positive effects of fertilizer on WUE if continuous cropping and no-tillage management are employed in the semiarid prairies.

Conclusions

In large parts of the world's dry areas, no irrigation water is available and yields of rain-fed crops are both low and uncertain. Food security in these areas is crucial, as 60% of the world's food insecure population living in drylands depends on crop agriculture and livestock for both food and income. While already exposed to climate extremes, the drylands, according to IPCC, are also likely to be severely hit by climate change.

Application of even small amounts of water in addition to rain can lead to a significant increase in the yields of crops in dry areas at high WUE, provided other factors such as plant nutrient availability are adequate. Several approaches can make such additional water available to crops from the local rainfall with low-cost low-risk land and water management techniques. Pitting or tied ridges, and by increasing surface roughness, infiltration can be increased and runoff can be used more productively. Maintaining a cover of crops or crop residues on the soil in a reduced-tillage system can be even more effective. Where adoption of these strategies is not possible, water harvesting approaches such as runoff farming may be followed to provide adequate moisture to the crop throughout the growing period. Capturing rainfall during a fallow period and storing it in the soil for use during the subsequent cropping period can also work where rainfall is distributed sparsely throughout the year. Application of manures can also improve water infiltration and WUE.

Sustained productivity under rain-fed conditions in dry areas is based on exploiting the synergy between soil and water conservation practices and supply of nutrients through mineral and organic sources. For many cropping systems, nutrient balances are negative indicating soil mining. A basic challenge to agricultural research and development is to better understand and arrest this trend. The use of fertilizers by a large number of smallholder farmers in dry areas remains low because of socioeconomic constraints. Increased deficiencies of N, P and other nutrients can be expected as a result of intensive cultivation and unbalanced fertilizer use. Locally available organic materials will continue to be used as sources of nutrients. Placement of fertilizers at a depth leads to high nutrient use efficiency but improved technologies/machines suitable for resource-poor farmers need to be developed. To avoid the application of excess fertilizer during the years of low rainfall, strategies such as 'response farming' which use early rainfall events to decide the amount of fertilizer for the approaching season and adjusting split fertilizer applications to the expected rainfall events, need to be advocated.

Future research pertaining to improvement in water and nutrient use efficiency in dry areas where mostly food-insecure farming families live should strive for active participation of farmers, longer time frames to fully evaluate residual effects and rigorous economic analysis of results. Research attention and development funding for rain-fed farming need to be increased.

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