Managing Water and Fertilizer for Sustainable Agricultural Intensification

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A reference guide to improve general understanding of the best management practices for the use of water and fertilizers throughout the world to enhance crop production, improve farm profitability and resource efficiency, and reduce environmental impacts related to crop production.

Edited by
Pay Drechsel
Patrick Heffer
Hillel Magen
Robert Mikkelsen
Dennis Wichelns

International Fertilizer Industry Association
28, rue Marbeuf, 75008 Paris, France
publications@fertilizer.org
www.fertilizer.org/library

International Water Management Institute
P.O. Box 2075, Colombo, Sri Lanka
iwmi@cgiar.org
www.iwmi.cgiar.org

International Plant Nutrition Institute
3500 Parkway Lane, Suite 550
Peachtree Corners, GA 30092, USA
info@ipni.net
www.ipni.net

International Potash Institute
Baumgärtlistrasse 17
P.O. Box 260, 8810 Horgen, Switzerland
ipi@ipipotash.org
www.ipipotash.org

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Foreword

Frank Rijsberman[1]

Ask anyone outside agriculture to describe the most important technological advance of the 20th century, and the likely suggestion will be something pertaining to computer technology or the internet. But ask an agricultural researcher, and you'll likely receive a very different answer. The most important advance of the 20th century was the Haber-Bosch process that enables the artificial manufacturing of nitrogen fertilizer to produce the food we need. It is fitting that both Fritz Haber and Carl Bosch were awarded Nobel Prizes in 1918 and 1931, respectively, for their work in chemistry and engineering.

Yet, crops cannot thrive by nitrogen alone. Long ago (in the 19th century) Carl Sprengel and Justus von Liebig put forth the Law of the Minimum, in which they described how plant growth is limited by the nutrient that is available in shortest supply. Thus, the crop response to additional increments of nitrogen might be nil if potassium or phosphorus or some other essential nutrient is limiting. The same can be said for soil moisture. Plant nutrients, alone, are not sufficient to grow or sustain plant growth without water, and vice versa. And in this day and age of increasing economic and physical water scarcity and an increasing portion of farm expenses attributed to chemical fertilizer, farmers must manage both inputs very closely to ensure they achieve high yields and obtain good returns on their investments, while reducing the possible negative impacts of water and nutrient use on the environment and ecosystem services.

Those of us working in academia, research institutes, and donor organizations must continue to enhance our understanding of agronomy, soil fertility and crop nutrition, and water management to feed the 9 billion people we are expecting by 2050. We need to increase adoption of existing techniques and develop new technologies and crop varieties, if we are to achieve the gains in food production needed. Affordable improvements in nutrient and water management will be especially crucial for the millions of smallholder households that struggle to produce sufficient food and income to sustain their precarious livelihoods in both rain-fed and irrigated settings. Sound agricultural development will remain the backbone for the achievement of many of the proposed Sustainable Development Goals from poverty alleviation to food security.

This book is a timely contribution as it cuts across the water and fertilizer sectors and summarizes the state-of-the-art knowledge on plant nutrition and water management and the challenges we face in achieving the food security component of the Sustainable Development Goals. The authors describe our current understanding of plant nutrient and water interactions, while looking ahead to the best management practices and innovations that will propel crop production to higher levels. The authors also address

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the issue of sustainability, as only those options that achieve food security and livelihood goals, while also protecting ecosystem services, will be acceptable in the 21st century.

We have come a long way since the remarkable insights and innovation provided by research pioneers in the 19th and 20th centuries. The fundamental principles of agronomy, plant science, and hydrology are well established and timeless. Yet, with increases in population and advances in economic growth, we face new challenges in each century, with regard to food security, livelihoods, and the environment. We can meet the challenges ahead, provided we continue to innovate and integrate our research programmes and transfer new knowledge effectively to farmers and other agriculturists seeking to optimize the interactions between plant nutrients, water, and other agricultural inputs in a sustainable manner. The same integration of efforts is required for those working on sustainable agricultural development at different scales. This book will inform and inspire those engaged in this pursuit.

Acknowledgements

List of abbreviations and symbols

List of abbreviations

AE	agronomic efficiency
AE_N	agronomic efficiency of fertilizer N
APP	amonium polyphosphate
AWD	alternate wetting and drying
BMP	best management practice
BNF	biological nitrogen fixation
CA	conservation agriculture
CAN	calcium ammonium nitrate
CBT	conservation bench terrace
CDI	controlled-deficit irrigation
CWU	consumptive water use
DAP	diammonium phosphate
DOM	dissolved organic matter
dS	deciSiemens
ET	evapotranspiration
EU	European Union
FA	fulvic acid
FK	fertilizer K
FN	fertilizer N
FNUE	fertilizer nitrogen use efficiency
FP	fertilizer P
FUE	fertilizer use efficiency
FYM	farmyard manure
GDP	gross domestic product
GIS	geographic information system
GM	gross margin
GWP	global warming potential
GY	grain yield
HA	humic acid
ha	hectare
hr	hour
IE	internal utilization efficiency
ISFM	integrated soil fertility management
km	kilometer
kg	kilogramme
l	litre

LAI	leaf area index
lb	pound
M	million
m³	cubic metre
MAP	monoammonium phosphate
MBT	mechanical-biological treatment
mg	milligramme
Mha	million hectares
ml	millilitre
mm	millimetre
Mt	million metric tonnes
NUE	nutrient use efficiency
PB	permanent bed
PE	physiological efficiency
PET	potential evapotranspiration
PFP	partial factor productivity
PNB	partial nutrient balance
Pr	precipitation
RE	apparent recovery efficiency
RIE	reciprocal internal efficiency
RLD	root length density
RWU	root water uptake
SAR	sodium adsorption ratio
SDI	subsurface drip irrigation
SGVP	standardized gross value of production
SOM	soil organic matter
SRI	system of rice intensification
SSA	sub-Saharan Africa
SSNM	site-specific nutrient management
t	metric tonne
TSP	triple superphosphate
TWW	treated wastewater
UAN	urea ammonium nitrate
USD	United States dollar
VPD	vapor pressure deficit
WANA	West Asia North Africa
WP	water productivity
WUE	water use efficiency
WW	municipal wastewaters
Y	yield
yr	year
ZT	zero-till

List of symbols

B	boron
Ca	calcium
CH_4	methane
Cl	chlorine
CO_2	carbon dioxide
Cu	copper
Fe	iron
H^+	hydrogen ion
HCO_3^-	bicarbonate
O_2	oxygen
OH^-	hydroxide
K	potassium
K_2O	oxide form of K, used in trade to express K content of fertilizer
KCl	potassium chloride
Mg	magnesium
N	nitrogen
^{15}N	nitrogen isotope
N_2	nitrogen gas
Na	sodium
N_2O	nitrous oxide
NO_3^-	nitrate
NH_3	ammonia
NH_4^+	ammonium
Mn	manganese
Mo	molybdenum
P	phosphorous
P_2O_5	oxide form of P, used in trade to express P content of fertilizer
S	sulphur
SO_4^{2-}	sulphate
Zn	zinc

Chapter 1

Managing water and nutrients to ensure global food security, while sustaining ecosystem services

Pay Drechsel[1], Patrick Heffer[2], Hillel Magen[3], Robert Mikkelsen[4], Harmandeep Singh[5] and Dennis Wichelns[6]

The world's cultivated area has grown by 12% over the last 50 years. Over the same period, the global irrigated area has doubled, accounting for most of the net increase in cultivated land (FAO, 2011), and world fertilizer use has increased more than five-fold (IFA, 2014). Driven by the fast expansion of irrigation and fertilizer consumption and the adoption of improved seeds and best management practices, which triggered a significant increase in the yields of major crops, agricultural production has grown between 2.5 and 3 times since the beginning of the 1960s (FAO, 2011).

While 2 litres of water are often sufficient for daily drinking purposes, it takes about 3,000 litres to produce the daily food needs of a person. Agriculture makes use of 70% of all water withdrawn from aquifers, streams and lakes. Globally, groundwater provides around 50% of all drinking water and 43% of all agricultural irrigation. Irrigated agriculture accounts for 20% of the total cultivated land but contributes 40% of the total food produced worldwide (FAO, 2011). In 2012, 179 million metric tonnes (Mt) of fertilizer (in nutrient terms) were applied to 1,563 million hectares (Mha) of arable land and permanent crops (FAO, 2014); i.e., an average application rate of 115 kg nutrients/ha. Global fertilizer consumption in 2012 was made of 109 Mt of nitrogen (N), 41 Mt of phosphate (P_2O_5) and 29 Mt of potash (K_2O). Asia is by far the main consuming region, with East Asia and South Asia accounting for 38 and 18%, respectively, of the world total. In contrast, Africa represents less than 3% of the world demand (IFA, 2014).

[1] International Water Management Institute (IWMI), Colombo, Sri Lanka, p.drechsel@cgiar.org
[2] International Fertilizer Industry Association (IFA), Paris, France, pheffer@fertilizer.org
[3] Interntional Potash Institute (IPI), Horgen, Switzerland, h.magen@ipipotash.org
[4] International Plant Nutrition Institute (IPNI), Norcross, GA, US, rmikkelsen@ipni.net
[5] Formerly International Plant Nutrition Institute (IPNI), Saskatoon, Canada, singh.harmandeep78@gmail.com
[6] Editor, Water Resources & Rural Development; Formerly, Senior Fellow, IWMI, dwichelns@mail.fresnostate.edu

FAO estimates that irrigated land in developing countries will increase by 34% by 2030, but the amount of water used by agriculture will increase by only 14%, thanks to improved irrigation management and practices. Access to water for productive agricultural use remains a challenge for millions of poor smallholder farmers, especially in sub-Saharan Africa, where the total area equipped for irrigation is only 3.2% of the total cultivated area (FAO, 2011). Farmer-driven, informal irrigation is in many regions more prominent than formal irrigation. Globally, fertilizer demand is projected to continue rising. It is forecast to reach about 200 Mt towards 2020 (Heffer and Prud'homme, 2014). Future growth will be influenced by nutrient use efficiency gains, which have been observed for three decades in developed countries, and since 2008 in China. Other Asian countries may follow the same trend in the years to come. In contrast, there are still large areas where farmers use little fertilizer and mine their soil nutrient reserves. This is particularly the case in sub-Saharan Africa, where farmers are estimated to have used 11 kg nutrients/ha in 2013, i.e. only 10% of the global average, but the region has witnessed the strongest growth rate since 2008.

The challenge of ensuring global food and nutrition security in future requires that we continue to increase the agricultural output. To this end, we must (a) intensify crop production on land already under cultivation, while preserving ecosystem services, and preventing further land degradation, and (b) carefully expand the area planted. We need to ensure that smallholder farmers have affordable access to the inputs needed to produce crops successfully for subsistence and for sale in local markets, as food insecurity is often caused by inadequate household income, rather than inadequate global food supply.

The question that must now be addressed is whether we can sustainably extend and intensify agricultural production. The reasons for this concern are the declining growth rates in crop yields in some areas, land degradation, increasing competition for water resources, declining soil nutrient levels, climate change, and pressure on biodiversity and ecological services, among others.

Global data describing efficiencies of nitrogen (N), phosphorus (P) and potassium (K) for major cereal crops from researcher-managed plots suggest that only 40 to 65% of the N fertilizer applied is utilized in the year of application. The first-year use efficiencies for K range from 30 to 50%, while those for P are lower (15 to 25%), in view of the complex dynamics of P in soils (Chapter 2 by Fixen *et al.*). However, applied P remains available to crops over long periods of time, often for a decade or longer. The common values for N efficiency on farmer-managed fields are less encouraging. When not properly managed, up to70 to 80% of the added N can be lost in rain-fed conditions and 60 to 70% in irrigated fields (Ladha *et al.*, 2005; Roberts, 2008). In contrast, N use efficiency levels close to those observed in research plots can be achieved by farmers when using precision farming techniques under temperate conditions in the absence of other limiting factors.

One of the key differences between researcher- and farmer-managed plots is that many farmers are less equipped to optimize nutrient and water use. This is essential, as both inputs are closely linked. Where current crop yields are far below their potential,

improvements in soil and nutrient management can generate major gains in water use efficiency (Molden, 2007).

Best management practices for improving fertilizer use efficiency include applying nutrients according to plant needs, placed correctly to maximize uptake, at an amount to optimize growth, and using the most appropriate source. These principles are reflected in nutrient stewardship programmes (e.g., 4R or the "four rights", viz. right source, at the right rate, at the right time, in the right place; IFA, 2009).

Using appropriate types and quantities of nutrients ('balanced fertilization') from mineral and organic sources is an essential practice for improving nutrient efficiency. For example, data colleced over many years and from many sites in China, India, and North America suggest that balanced fertilization with appropriate N, P, and K increases first-year recoveries by an average of 54%, compared with average recoveries of 21% when only N is applied (Fixen *et al.*, 2005). However, many farmers do not practice balanced fertilization due to lack of knowledge or financial capacity, or due to logistic constraints.

Improvements in nutrient use efficiency should not be viewed only as fertilizer management. For example, the processes of nutrient accumulation or depletion are often related to transport processes in water. The interaction of water and nutrients in soil fertility management is governed by the following considerations:

- Soil water stress will limit soil nutrient use at the plant level.
- Soil-supplied nutrients can be taken up by plants only when sufficient soil solution allows mass flow and diffusion of nutrients to roots.
- Soil water content is the single most important factor controlling the rate of many chemical and biological processes, which influence nutrient availability.

Poor soil fertility limits the ability of plants to efficiently use water (Bossio *et al.*, 2008). For example, in the African Sahel, only 10 to 15% of the rainwater is used for plant growth, while the remaining water is lost through run-off, evaporation and drainage. This low water utilization is partly because crops cannot access it, due to lack of nutrients for healthy root growth (Penning de Vries and Djiteye, 1982). For example, Zaongo *et al.* (1997) reported that root density of irrigated sorghum increased by 52% when N fertilizer was applied, compared with application of only water. Similarly, Van Duivenbooden *et al.* (2000) provide a comprehensive list of options to improve water use efficiency in the Sahel. Thus, even in dry environments, where water appears to be the limiting factor for plant growth, irrigation alone may fail to boost yields without consideration of the soil and its nutrient status.

Water management is central to producing the world's food supply, and water scarcity has become a major concern in many regions. Rijsberman (2004) and Molden (2007) provide the following observations:

(a) There is broad agreement that increasing water scarcity will become the key limiting factor in food production and economic livelihood for poor people throughout rural Asia and most of Africa. Particularly severe scarcity is anticipated in the breadbaskets of northwest India and northern China.

(b) Latin-America is relatively water-abundant at the national level, and is not generally considered to be water scarce. However, when viewed from the perspective of "economic water scarcity," there is a notable need for investments in the water sector,

(c) Most small islands in the Caribbean and Pacific regions are water scarce and will face increasing water shortage in future.

There are two major approaches to improving and sustaining productivity under water-scarce conditions: (a) modifying the soil environment by providing irrigation and reducing water loss, and (b) modifying plants to suit the environment through genetic improvements. Both these approaches have achieved success in improving water use efficiency to varying degrees, depending on the region and the crop. Irrigation has played a large role in improving crop yields and extending food supplies across key production regions, such as the Indo-Gangetic Plain, and the deltaic areas of South and Southeast Asia. However, many opportunities remain for improvement in these and other regions.

Globally, an estimated 70% of water withdrawals from rivers, lakes and groundwater is allocated to, or used in, agriculture. Much of that water is used consumptively, while much also runs off to streams or percolates into aquifers. Some of the water in runoff and deep percolation is used again by other farmers, or may generate in-stream flow. Drip and sprinkler systems can substantially reduce run-off and deep percolation; and drip irrigation can also reduce evaporation. However, those systems – where available – do not necessarily reduce consumptive use per unit area. Rather, they can lead to higher rates of consumptive use through improvements in distribution uniformity and by reducing periods of moisture stress. For these reasons, modern irrigation techniques do not always 'save water' in a general sense, but they can reduce the loss of water to evaporation from soil surfaces or water transpired by non-beneficial vegetation. Such methods should be viewed primarily as measures for improving water management including labour reduction while enhancing crop production, rather than measures for saving water.

At present up to 20 Mha, nearly 10% of the world's permanently irrigated land, are estimated to be irrigated with treated, untreated, or diluted wastewater. In most cases, farmers have no alternative, as their water sources are polluted, but in an increasing number of countries wastewater use is a planned objective, boosted by current climate change predictions (Scott *et al.*, 2010). For example, policy decisions in Israel have enabled farmers to obtain sufficient irrigation supply from treated wastewater. The recovery and reuse of wastewater from agricultural, industrial, and municipal sources will increase in future as a result of increasing competition for limited water supplies. One goal for agricultural research is to determine the best method for utilizing treated and untreated wastewaters, while minimizing risk to irrigators, farm families, and consumers. This challenge extends to the recovery of nutrients from wastewater, which can take place on-farm or during the water treatment process.

Water and nutrient use within plants are closely linked. A plant with adequate nutrition can generally better withstand water stress (Gonzalez-Dugo *et al.*, 2010; Waraich *et al.*, 2011). For example, in rain-fed settings, farmers gain yield by applying

nitrogen in conjunction with expected rainfall. Phosphorus applied at early stages of plant development can promote root growth, which is helpful in accommodating water stress. Potassium plays a key role in stomata and osmotic regulation. Plant nutrients and water are complementary inputs, and plant growth response to any nutrient or to water is a function of the availability of other inputs. Thus, the incremental return to fertilizer inputs is larger when water is not limiting, just as the incremental return to irrigation generally is larger when nutrients are not limiting. Smallholder farmers must also consider risk and uncertainty when determining whether or not to apply fertilizer, particularly in rain-fed settings. If rainfall is inadequate or late in arriving, the investment in fertilizer might generate no return. Thus, to be meaningful, the metrics used to express the performance of agricultural inputs, such as fertilizer use efficiency and water productivity, should be analyzed together, and in combination with complementary indicators reflecting the overall effectiveness of the farming system, including crop yield and soil nutrient levels.

Wise management of water, fertilizer, and soil is critical in sustainable food production. Such management can increase food production and enhance environmental quality if ecosystems and their services receive sufficient attention. Unfortunately, the long-term benefits of an integrated approach may not be immediately obvious for farmers or businesses making short-term decisions. While farmers may have a shorter time horizon, extension systems lack capacity, and markets often do not properly account for long-term implications of current management decisions. As a result, some appropriate technologies that could increase yields and conserve soil, water, and nutrients are not being implemented on agricultural fields. Additional understanding regarding adoption constraints and incentives to alleviate these constraints will enhance efforts to promote farm-level use of integrated innovative crop production methods.

Another constraint on advances in water and nutrient management is the fragmentation of research efforts, along with the lack of a rational system for sharing research information across the water and nutrient disciplines. Insufficient attention has been given to the identification of integrated research priorities and the development of strategies to carry out coordinated scientific investigations. In many countries, soil and crop research institutions remain as separate entities. While additional financial support will be needed for this type of reform, much can be done to better plan and coordinate ongoing water and nutrient management studies.

Advances in conventional breeding and biotechnology will lead to continuing improvements in crop genetics. New varieties might gain improved capacities to extract nutrients and water from the soil and thereby achieve higher yields with fewer inputs per unit harvested product. However, the nutrients must be supplied from a reliable and affordable source. The advantages of higher-yielding plant varieties is usually clear to farmers, while the required changes in soil and water management are often less obvious and require more time and greater effort to achieve widespread use.

Improvements in crop genetics, the spread of irrigation, and the increase in plant nutrient use will contribute to efforts to feed, clothe, and provide fuel and building materials for an increasing and wealthier global population. Yet, we must continue to integrate these factors into viable strategies and policies.

This book reviews concepts and practices currently followed in different regions of the world for efficient water and nutrient management, and the promise they hold for a sustainable agriculture. Water and nutrients are critical and often they are physically or economically scarce inputs in crop production. The chapters in this book explain the issues and strategies related to efficient and effective water and nutrient management by defining broad guidelines and principles that can be adapted to region-specific needs. The chapters also describe how such research can be integrated with genetic improvement and systems management. While some chapters are more focused on the nutrient component or on the water component of the agro-ecosystem, it is important to keep in mind the need for critical linkages operating in the background.

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Chapter 2

Nutrient/fertilizer use efficiency: Measurement, current situation and trends

Paul Fixen[1], Frank Brentrup[2], Tom W. Bruulsema[3], Fernando Garcia[4], Rob Norton[5] and Shamie Zingore[6]

Abstract

Nutrient use efficiency (NUE) is a critically important concept in the evaluation of crop production systems. It can be greatly impacted by fertilizer management as well as by soil- and plant-water management. The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field. NUE addresses some, but not all, aspects of that performance. Therefore, system optimization goals necessarily include overall productivity as well as NUE. The most appropriate expression of NUE is determined by the question being asked and often by the spatial or temporal scale of interest for which reliable data are available. In this chapter, we suggest typical NUE levels for cereal crops when recommended practices are employed; however, such benchmarks are best set locally within the appropriate cropping system, soil, climate and management contexts. Global temporal trends in NUE vary by region. For N, P and K, partial nutrient balance (ratio of nutrients removed by crop harvest to fertilizer nutrients applied) and partial factor productivity (crop production per unit of nutrient applied) for Africa, North America, Europe, and the EU-15 are trending upwards, while in Latin America, India, and China they are trending downwards. Though these global regions can be divided into two groups based on temporal trends, great variability exists in factors behind the trends within each group. Numerous management and environmental factors, including plant water status, interact to influence NUE. Similarly, plant nutrient status can markedly influence water use efficiency. These relationships are covered in detail in other chapters of this book.

[1] International Plant Nutrition Institute (IPNI), Brookings, SD, US, pfixen@ipni.net
[2] Yara Research Centre Hanninghof, Dülmen, Germany, frank.brentrup@yara.com
[3] International Plant Nutrition Institute (IPNI), Guelph, Canada, tom.bruulsema@ipni.net
[4] International Plant Nutrition Institute (IPNI), Buenos Aires, Argentina, fgarcia@ipni.net
[5] International Plant Nutrition Institute (IPNI), Horsham, Victoria, Australia, rnorton@ipni.net
[6] International Plant Nutrition Institute (IPNI), c/o IFDC., Nairobi, Kenya, szingore@ipni.net

The concept and importance of NUE

Meeting societal demand for food is a global challenge as recent estimates indicate that global crop demand will increase by 100 to 110% from 2005 to 2050 (Tilman *et al.*, 2011). Others have estimated that the world will need 60% more cereal production between 2000 and 2050 (FAO, 2009), while others predict food demand will double within 30 years (Glenn *et al.*, 2008), equivalent to maintaining a proportional rate of increase of more than 2.4% per year. Sustainably meeting such demand is a huge challenge, especially when compared to historical cereal yield trends which have been linear for nearly half a century with slopes equal to only 1.2 to 1.3% of 2007 yields (FAO, 2009). Improving NUE and improving water use efficiency (WUE) have been listed among today's most critical and daunting research issues (Thompson, 2012).

NUE is a critically important concept for evaluating crop production systems and can be greatly impacted by fertilizer management as well as soil- and plant-water relationships. NUE indicates the potential for nutrient losses to the environment from cropping systems as managers strive to meet the increasing societal demand for food, fiber and fuel. NUE measures are not measures of nutrient loss since nutrients can be retained in soil, and systems with relatively low NUE may not necessarily be harmful to the environment, while those with high NUE may not be harmless. We will provide examples of these situations later in the chapter that illustrate why interpretation of NUE measurements must be done within a known context.

Sustainable nutrient management must be both efficient and effective to deliver anticipated economic, social, and environmental benefits. As the cost of nutrients climb, profitable use puts increased emphasis on high efficiency, and the greater nutrient amounts that higher yielding crops remove means that more nutrient inputs will likely be needed and at risk of loss from the system. Providing society with a sufficient quantity and quality of food at an affordable price requires that costs of production remain relatively low while productivity increases to meet projected demand. Therefore, both productivity and NUE must increase. These factors have spurred efforts by the fertilizer industry to promote approaches to best management practices for fertilizer such as 4R Nutrient Stewardship, which is focused on application of the right nutrient source, at the right rate, in the right place and at the right time (IPNI, 2012b) or the Fertilizer Product Stewardship Program (Fertilizers Europe, 2011). These approaches consider economic, social, and environmental dimensions essential to sustainable agricultural systems and therefore provide an appropriate context for specific NUE indicators.

NUE appears on the surface to be a simple term. However, a meaningful and operational definition has considerable complexity due to the number of potential nutrient sources (soil, fertilizer, manure, atmosphere [aerial deposition], etc.), and the multitude of factors influencing crop nutrient demand (crop management, genetics, weather). The concept is further stressed by variation in intended use of NUE expressions and because these expressions are limited to data available rather than the data most appropriate for interpretation.

The objective of nutrient use and nutrient use efficiency

The objective of nutrient use is to increase the overall performance of cropping systems by providing economically optimum nourishment to the crop while minimizing nutrient losses from the field and supporting agricultural system sustainability through contributions to soil fertility or other components of soil quality. NUE addresses some, but not all, aspects of that performance (Mikkelsen *et al.*, 2012). The most valuable NUE improvements are those contributing most to overall cropping system performance.

Therefore, management practices that improve NUE without reducing productivity or the potential for future productivity increases are likely to be most valuable. If the pursuit of improved NUE impairs current or future productivity, the need for cropping fragile lands will likely increase. Fragile lands usually support systems with lower NUE that also use water less efficiently. At the same time, as nutrient rates increase towards an optimum, productivity continues to increase but at a decreasing rate, and NUE typically declines (Barbieri *et al.*, 2008). The extent of the decline will be determined by source, time, and place factors, other cultural practices, as well as by soil and climatic conditions.

Intended use and available data for NUE expressions

The most appropriate NUE expression is determined by the question being asked and often by the spatial or temporal scale of primary interest for which reliable data are available. The scale of interest may be as small as an individual plant for a plant breeder or geneticist or as large as a country or set of countries for policy purposes, educators or marketers. Questions of interest may be focused on a singular practice or product during a single growing season or on a cropping system over a period of decades. Data available may be relatively complete, accounting for all major nutrient inputs and specific nutrient losses in an intensive research project, or limited to those generally available to nutrient managers.

A multitude of expressions and measurements have evolved to meet the needs of this diverse set of circumstances and all are commonly referred to as "NUE". To be appropriately interpreted, the specific method used must be stated.

Common measures of NUE and their application

An excellent review of NUE measurements and calculations was written by Dobermann (2007). Table 1 is a summary of common NUE terms, as defined by Dobermann, along with their applications and limitations. The primary question addressed by each term and the most typical use of the term are also listed.

Partial factor productivity (PFP) is a simple production efficiency expression, calculated in units of crop yield per unit of nutrient applied. It is easily calculated for any farm that keeps records of inputs and yields. It can also be calculated at the regional and national level, provided reliable statistics on input use and crop yields are available. However, partial factor productivity values vary among crops in different

cropping systems, because crops differ in their nutrient and water needs. A comparison between crops and rotations is particularly difficult if it is based on fresh matter yields, since these differ greatly depending on crop moisture contents (e.g. potato vs cereals). Therefore, geographic regions with different cropping systems are difficult to compare with this indicator.

Table 1. Common NUE terms and their application (after Dobermann, 2007).

Term	Calculation*	Question addressed	Typical use
Partial factor productivity	$PFP = Y/F$	How productive is this cropping system in comparison to its nutrient input?	As a long-term indicator of trends.
Agronomic efficiency**	$AE = (Y-Y_0)/F$	How much productivity improvement was gained by use of nutrient input?	As a short-term indicator of the impact of applied nutrients on productivity. Also used as input data for nutrient recommendations based on omission plot yields.
Partial nutrient balance	$PNB = U_H/F$	How much nutrient is being taken out of the system in relation to how much is applied?	As a long-term indicator of trends; most useful when combined with soil fertility information.
Apparent recovery efficiency by difference**	$RE = (U-U_0)/F$	How much of the nutrient applied did the plant take up?	As an indicator of the potential for nutrient loss from the cropping system and to access the efficiency of management practices.
Internal utilization efficiency	$IE = Y/U$	What is the ability of the plant to transform nutrients acquired from all sources into economic yield (grain, etc.)?	To evaluate genotypes in breeding programs; values of 30-90 are common for N in cereals and 55-65 considered optimal.
Physiological efficiency**	$PE = (Y-Y_0)/(U-U_0)$	What is the ability of the plant to transform nutrients acquired from the source applied into economic yield?	Research evaluating NUE among cultivars and other cultural practices; values of 40-60 are common.

* Y = yield of harvested portion of crop with nutrient applied; Y_0 = yield with no nutrient applied; F = amount of nutrient applied; U_H = nutrient content of harvested portion of the crop; U = total nutrient uptake in aboveground crop biomass with nutrient applied; U_0 = nutrient uptake in aboveground crop biomass with no nutrient applied; Units are not shown in the table since the expressions are ratios on a mass basis and are therefore unitless in their standard form. P and K can either be expressed on an elemental basis (most common in scientific literature) or on an oxide basis as P_2O_5 or K_2O (most common within industry).
** Short-term omission plots often lead to an underestimation of the long-term AE, RE or PE due to residual effects of nutrient application.

Agronomic efficiency (AE) is calculated in units of yield increase per unit of nutrient applied. It more closely reflects the direct production impact of an applied fertilizer and relates directly to economic return. The calculation of AE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. If it is calculated using data from annual trials rather than long-term trials, NUE of the applied fertilizer is often underestimated because of residual effects of the application on future crops. Estimating long-term contribution of fertilizer to crop yield requires long-term trials.

Partial nutrient balance (PNB) is the simplest form of nutrient recovery efficiency, usually expressed as nutrient output per unit of nutrient input (a ratio of "removal to use"). Less frequently it is reported as "output minus input." PNB can be measured or estimated by crop producers as well as at the regional or national level. Often, the assumption is made that a PNB close to 1 suggests that soil fertility will be sustained at a steady state. However, since the balance calculation is a partial balance and nutrient removal by processes, such as erosion and leaching are usually not included, using a PNB of 1 as an indicator of soil fertility sustainability can be misleading, particularly in regions with very low indigenous soil fertility and low inputs and production, such as in sub-Saharan Africa. Also, all nutrient inputs are rarely included in the balance calculations, thus the modifier, partial, in the term. Biological N fixation, recoverable manure nutrients, biosolids, irrigation water, and the atmosphere can all be nutrient sources in addition to fertilizer. Values well below 1, where nutrient inputs far exceed nutrient removal, might suggest avoidable nutrient losses and thus the need for improved NUE (Snyder and Bruulsema, 2007); attainable values, however, are cropping system and soil specific. A PNB greater than 1 means more nutrients are removed with the harvested crop than applied by fertilizer and/or manure, a situation equivalent to "soil mining" of nutrients. This situation may be desired if available nutrient contents in the soil are known to be higher than recommended. However, in cases where soil nutrient concentration is at or below recommended levels, a PNB >1 must be regarded as unsustainable (Brentrup and Palliere, 2010). Over the short term and on individual farms, PNB can show substantial fluctuations due to cash flow and market conditions, especially for P and K. Longer-term assessment of PNB over several years is therefore more useful.

Apparent recovery efficiency (RE) is one of the more complex forms of NUE expressions and is most commonly defined as the difference in nutrient uptake in the aboveground parts of the plant between the fertilized and unfertilized crop relative to the quantity of nutrient applied. It is often the preferred NUE expression by scientists studying the nutrient response of the crop. Like AE, it can only be measured when a plot without nutrient has been used on the site, but in addition requires measurement of nutrient concentrations in the crop. And, like AE, when calculated from annual response data, it will often underestimate long-term NUE.

Internal utilization efficiency (IE) is defined as the yield in relation to total nutrient uptake. It varies with genotype, environment and management. A very high IE suggests deficiency of that nutrient. Low IE suggests poor internal nutrient conversion due to other stresses (deficiencies of other nutrients, drought stress, heat stress, mineral toxicities, pests, etc.).

Physiological efficiency (PE) is defined as the yield increase in relation to the increase in crop uptake of the nutrient in aboveground parts of the plant. Like AE and RE, it needs a plot without application of the nutrient of interest to be used on the site. It also requires measurement of nutrient concentrations in the crop and is mainly measured and used in research.

NUE application and benchmarks

In most cases it is helpful to use more than one NUE term when evaluating any management practice, allowing for a better understanding and quantification of the crop response to the applied nutrient. The different indicators should be used simultaneously. Frequently, the highest AE is obtained at the lowest fertilizer rates being evaluated, rates associated with high PNB. Genetic modifications, such as the recent discovery of the Phosphorus Starvation Tolerance gene that helps rice access more soil P (IRRI, 2012), will increase PFP and P removal in crop harvest. Such a development has great short-term value to farmers and may allow the system to operate at a lower level of soil P. However, if P use is less than the enhanced removal level, soil P depletion does occur (PNB is greater than 1). Therefore, even with such genetic changes, an appropriate PNB must be attained for system sustainability. Although individual NUE terms can each be used to describe the efficiency of fertilizer applications, a complete analysis of nutrient management should include other NUE terms, grain yield, fertilizer rates, and native soil fertility (Olk *et al.*, 1999). For example, under low soil P availability, AE for P could be very high with low P rates; however, PNB for P under this condition could be well above 1, depleting the already low soil P reserves as shown in Figure 8. In this case, a low P rate with high AE for P, though a better practice than no P application at all, would not be considered a best management practice (BMP).

This chapter will illustrate the great variability existing in the major NUE measures and trends and the primary factors affecting them. Improvement in nutrient stewardship can be facilitated by identifying relevant measures of NUE for the scale of interest, collecting data for those measures, then having benchmarks for evaluating the collected data. Benchmarks are best set locally within the appropriate cropping system, soil, climate and management context and with full knowledge of how NUE measures are being calculated. However, the focus of this chapter is to provide general guidelines for interpreting NUE measures. Table 2 provides such generalized guidelines for the most common NUE measures for N, P and K for cereal crops. These benchmarks should be replaced with levels based on local research and experience whenever possible.

Table 2. Typical NUE levels for cereal crops (primarily maize, rice, and wheat) when recommended management practices are employed and where soil available P and K levels are currently within a recommended range.

Measure	Typical level***			Interpretation
	N	P (P_2O_5)	K (K_2O)	
Partial factor productivity (kg grain (kg nutrient)$^{-1}$)	40-90	100-250 (45-110)	75-200 (60-165)	Lower levels suggest less responsive soils or over application of nutrients while higher levels suggest that nutrient supply is likely limiting productivity.
Agronomic efficiency* (kg grain (kg nutrient)$^{-1}$)	15-30	15-40 (7-15)	8-20 (7-15)	Lower levels suggest changes in management could increase crop response or reduce input costs.
Recovery efficiency* (%)	40-65	15-25	30-50	Lower levels suggest changes in management could improve efficiency or that nutrients are accumulating in the soil.
Partial nutrient balance** (kg grain (kg nutrient)$^{-1}$)	0.7-0.9	0.7-0.9	0.7-0.9	Lower levels suggest changes in management could improve efficiency or soil fertility could be increasing. Higher levels suggest soil fertility may be declining.

* Based on first year response.
** Inputs include fertilizer, applied manure nutrients, and nutrients in irrigation water.
*** Ranges were selected by the authors based on reported values in the published literature and best judgment on what typical levels are when practices recommended for the region are being followed. These values should be replaced with levels based on local research and experience whenever possible.

NUE at different scales

The NUE terms in Table 1 could be estimated at scales ranging from global to small areas within individual fields. Scalability is a desired attribute for performance indicators, because it makes linkages clearer between local management practices and larger-scale impacts. However, the certainty and reliability of the estimation for specific sites decrease as the scale increases. In any case, these estimates depend on the quality of the data used in calculations. Simpler indicators such as PFP scale more easily than complex forms such as RE and PE. Several examples of NUE terms applied at different scales follow.

Regional scale
Table 3 shows estimations of PFP and PNB for N for cereal crops of regions of the world sorted from lowest to highest average N rate. Regions differ considerably in these two

measures of efficiency, with the two highest values occurring for the regions with the lowest N rates, Africa and Eastern Europe/Central Asia. These regions also have the lowest average yields and PNB values much greater than one, indicative of systems that are possibly mining N from soil organic matter and may not be sustainable (unless there are substantial contributions of N from rotational legumes, not taken into account in these PNB or PFP values).

Table 3. Partial factor productivity and partial nutrient balance for N applied to cereals for world regions and associated average fertilizer N rates and crop yields.

Region	N rate (kg ha^{-1})	Cereal yield (t ha^{-1})	Grain N* (kg ha^{-1})	PFP (kg grain (kg N)$^{-1}$)	PNB (kg grain N (kg N)$^{-1}$)
Sub-Saharan Africa	9	1.1	17	122	1.8
Eastern Europe, Central Asia	25	2.1	32	84	1.3
Oceania	48	1.9	29	40	0.59
Latin America	55	2.9	44	53	0.79
South Asia	58	2.4	36	41	0.62
Southeast Asia	65	3.2	48	49	0.74
West Asia, North Africa	68	2.3	35	34	0.51
Northeast Asia (Japan, S. Korea)	89	6.1	92	69	1.03
North America	112	5.1	77	46	0.68
Western Europe	113	5.5	83	49	0.73
East Asia (China, Vietnam, Korea DPR)	155	4.8	72	31	0.46
World	70	3.1	47	44	0.66

*Assuming 15 kg N t^{-1} of cereal grain.
Fertilizer N rate and cereal yield for years 1999-2002/03 reported by Dobermann and Cassman, 2005.

The values in Table 3 represent very large regions and are averages across great variability. Sub-Saharan Africa (SSA), even with the extremely high average PNB, has great intercountry variability with generally higher values in the east and lower values in the central and western parts of the continent (Smaling *et al.*, 1997). We also must recognize the high variability in PNB among farms within countries in SSA. Farms having good access to resources will have PNB values often less than 1 (nutrient input exceeds removal) while those with fewer resources will be greater than 1 as the aggregate data of Table 3 reflect (Zingore *et al.*, 2007). Farms with lower access to resources often rely more on N from legumes, an effect that is not captured in Table 3. East Asia shows the lowest PNB (0.46) at the highest average N input rate. This suggests the potential for
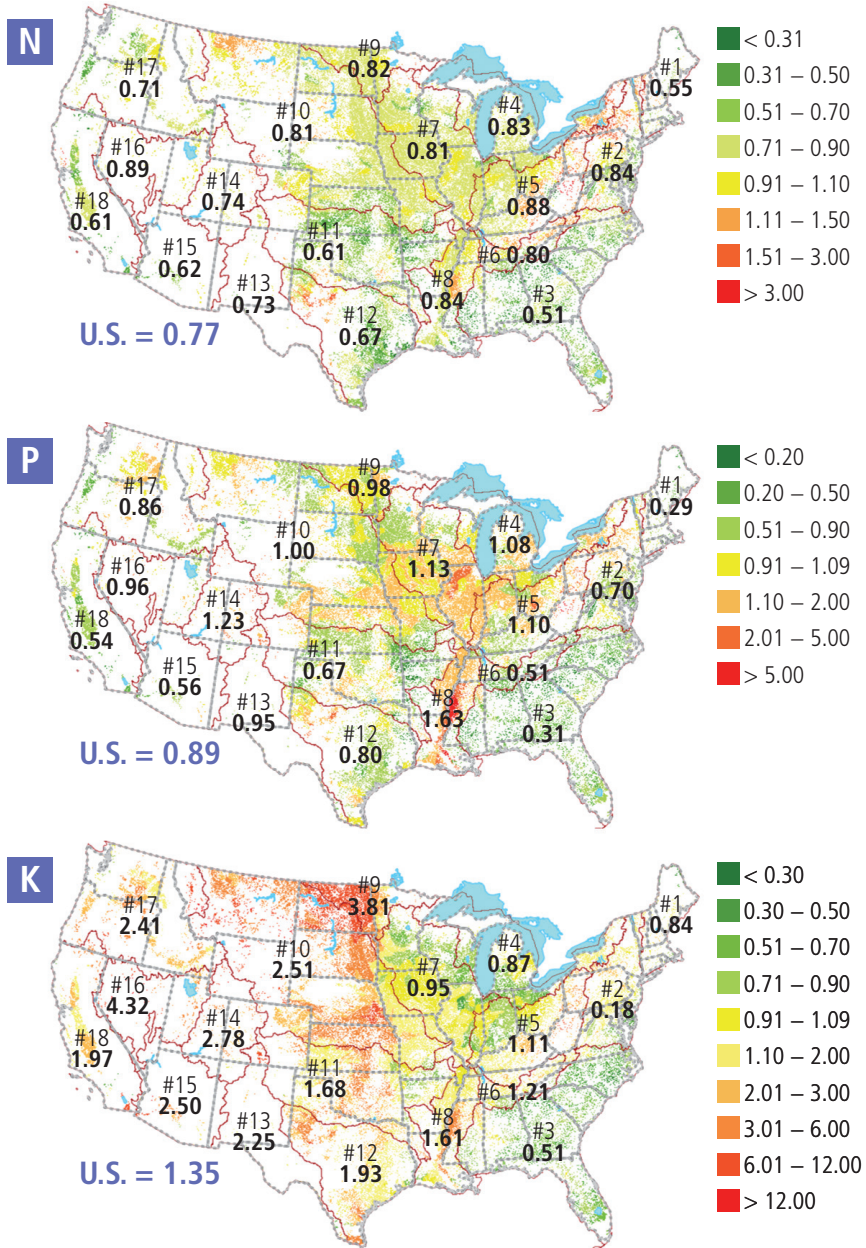
Partial nutrient balance, 2007 (mean nutrient content of harvested crops for 2006-2008 divided by the sum of farm fertilizer applied, recoverable manure nutrients, and biological N fixation for 2007).

Figure 1. Partial nutrient balance for watershed regions of the US (IPNI, 2012a).

improving NUE while maintaining productivity. At this very coarse scale, differences among other regions in Table 3 can be due to a complex set of factors including crop rotation, soil properties, climate, government policy, and management intensity.

The regional differences in PNB within a single country illustrate the impact of this complex set of factors on NUE. For example, PNB for watershed regions of the US varies in a somewhat predictable fashion (Figure 1).The PNB values in Figure 1 are less "partial" than those in Table 3 since they include both N fixation and applied manure nutrients. PNB levels for N, P and K are generally low in the southeast US (Region 3), dominated by coarse-textured, low organic matter soils, which have very low water-holding and cation exchange capacities. Much of this region also produces high-value crops, many of them inefficient nutrient users. At the other extreme is K in the western half of the country where PNB levels are extremely high due to generally high indigenous soil K levels resulting in infrequent response to K fertilization. Such factors need to be considered when interpreting NUE data at regional scales.

Farm or field scale

The PFP and PNB provide useful information for growers and can also be calculated for any farm that keeps records of inputs and outputs. Figure 2 shows trends in fertilizer use per ha and per ton of grain for a farm in Brazil and illustrates the kind of data often available at a farm scale. In this case, though fertilizer use per ha increased, PFP also increased (plotted as its inverse, kg of NPK per ton of crop yield) due to the accompanying increase in crop yields. Improvements in agronomic practices of a cropping system can markedly influence NUE and when implemented concurrently with increased nutrient rates can result in simultaneous increases in fertilizer rates, crop yields and NUE ("sustainable intensification").
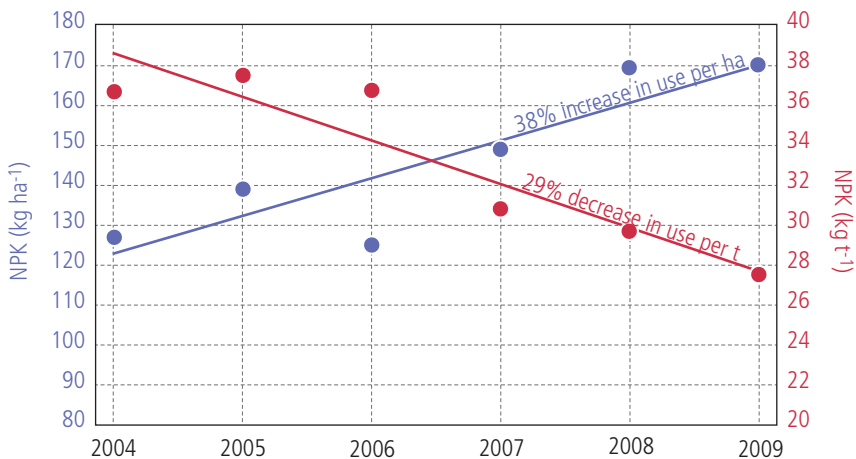
Figure 2. Evolution of fertilizer use per ha and per tonne (t) of crop yield in a farm near Itiquira, MT, Brazil (L. Prochnow, personal communication, 2012).

Neither PFP nor PNB indicators consider inherent soil nutrient supplies; thus they do not fully reflect the true efficiency of fertilizer-derived nutrients. The short-term NUE of applied nutrients is better estimated using AE, RE and PE, but these indices require data that are not often available at a farm scale.

The use of a check plot or omission plot has traditionally been limited to research settings, but could be established on the farm if a grower has interest. There is merit to establishing both perennial check plots, where the same area remains without the application of fertilizers across years and that will reflect the long-term contribution of applied nutrients to productivity and soil quality, as well as annual check plots, where the response of a single crop to a nutrient application can be assessed. Such on-farm research is best done in cooperative groups, since inclusion of check plots can be costly to the grower in terms of lost yield and the loss of uniformity in quality of harvested product. This is an especially important limitation for check- plot establishment where severe deficiencies exist such as in SSA. Also, shared results of on-farm research conducted across a production area are more meaningful than single observations.

Plot–scale research

Research plots typically offer a full complement of data on nutrient uptake and removal in crop harvest for plots with and without the application of fertilizers, enabling calculation of all the common NUE forms (Table 1). Because each term addresses different questions and has different interpretations, research reports often include measurements of more than one NUE expression (Dobermann, 2007). A summary of NUE measurements from numerous field trials on rice, wheat and maize in China is shown in Table 4 and from wheat field trials in three regions of China in Table 5. The regional wheat data illustrate the great differences that exist in NUE among regions within countries due to differences in climate, soil properties and cropping systems.

Table 4. Average yield response and NUE for field trials in China from 2002 to 2006 (Jin, 2012).

Crop	Nutrient	Number of trials	Average rate of fertilizer use (kg ha^{-1})	Yield increase (%)	AE (kg kg^{-1})	RE (%)
Rice	N	51	187	40	12	25
Wheat	N	30	181	43	11	36
Maize	N	70	219	38	12	31
Rice	P	62	41	13	26	10
Wheat	P	39	52	24	21	16
Maize	P	71	49	15	26	15
Rice	K	67	122	21	11	25
Wheat	K	51	100	18	8	26
Maize	K	84	118	17	13	32

Table 5. A comparison of NUE expressions based on the optimal treatment from wheat field trials in three regions of China between 2000 and 2008 (Liu *et al.*, 2011).

Region*	Nutrient	Number of obser- vations**	Average rate of fertilizer use (kg ha^{-1})	PFP*** (kg kg^{-1})	AE (kg kg^{-1})	RE (%)	PNB**** (kg kg^{-1})
NC	N	122-210	199	38(518)	9.5	35.2	1.10
LY	N	60-155	220	34(234)	11.3	48.1	0.81
NW	N	13-34	169	37(108)	6.5	17.0	0.70
Average	**N**	**195-363**		**36(860)**	**9.8**	**37.9**	**0.95(0.73)**
NC	P	46-137	56	142(506)	23.0	17.8	1.07
LY	P	26-51	47	146(220)	18.4	25.9	0.91
NW	P	11-40	47	142(108)	7.0	7.4	0.43
Average	**P**	**83-223**		**143(834)**	**19.2**	**19.0**	**0.96(0.81)**
NC	K	70-374	111	71(481)	7.6	23.7	1.67
LY	K	26-69	96	76(234)	8.3	34.2	1.73
NW	K	14-77	70	66(102)	4.2	30.0	2.73
Average	**K**	**110-517**		**72(817)**	**7.2**	**27.0**	**1.82(0.60)**

*NC: North central with temperate climate and winter wheat-maize annual rotation; LY: Lower Yangtze River with temperate to subtropical humid climate and predominant rice-wheat rotation; NW: Nor-thwest with continental climate and continuous spring wheat cropping system;
**range in observations for AE, RE and PNB;
***Number of observations for PFP in parentheses;
****Calculated as removal in grain and straw divided by applied fertilizer except values in parentheses where only grain removal are included. An average of 44% of wheat straw nutrient is returned to the field in China.

Estimates of NUE calculated from research plots on experimental stations are generally greater than those for the same practices applied by farmers in production fields (Cassman *et al.*, 2002; Dobermann, 2007). Differences in scale between research plots and whole fields for management of fertilizer practices, tillage, seeding, pest management, irrigation and harvest contribute to these differences.

Determination of RE in research plots is usually done by the difference calculations described in Table 1. An alternative method for N involves using the ^{15}N isotope as a tracer in the fertilizer to determine the proportion of fertilizer applied that was taken up by the crop. The two methods are usually related; however, RE determined by the ^{15}N method will be usually lower than the different estimates due to cycling of the ^{15}N through microbially-mediated soil processes (Cassman *et al.*, 2002). Tracers are more useful when recovery is measured in the soil as well as in the plant, particularly in the longer term. Ladha *et al.* (2005) summarized results from several studies where ^{15}N was

used to estimate N recovery by five subsequent crops, reporting a range of 5.7 to 7.1%, excluding the first growing season. With the first growing season, total RE ranged from 35 to 60%.

Current status and trends in NUE for N

Current status of NUE for N

Ladha *et al.* (2005) conducted an extensive review of 93 published studies where NUE was measured in research plots (Table 6). This review provides estimates of the central tendency for NUE expressions for maize, wheat and rice. Values for PFP and AE were generally higher for maize and rice than for wheat, at least in part due to the higher N content of wheat grain. Values for RE varied widely across regions and crops with a 10th percentile value of 0.2 and a 90th percentile value of 0.9 (grain plus straw). Much of the range in values was attributed to variations among studies in soil, climate and management conditions. The overall average RE of 55% compares well with other published global estimates of 50% by Smil (1999) and 57% by Sheldrick *et al.* (2002) and with estimates for the US and Canada of 56% by Howarth *et al.* (2002) and 52% by Janzen *et al.* (2003) as summarized in Ladha *et al.* (2005).

Table 6. Common NUE values for N for maize, wheat, and rice and for various world regions in 93 published studies conducted in research plots compiled by Ladha *et al.* (2005).

Crop or region	Number of observa-tions*	Average rate of ferti-lizer use ($kg\ ha^{-1}$)	PFP** ($kg\ kg^{-1}$)	AE** ($kg\ kg^{-1}$)	RE** (%)	PE** ($kg\ kg^{-1}$)
Maize	35-62	123	72(6)	24(7)	65(5)	37(5)
Wheat	145-444	112	45(3)	18(4)	57(4)	29(4)
Rice	117-187	115	62(3)	22(3)	46(2)	53(3)
Africa	2-24	139	39(11)	14(6)	63(5)	23(6)
Europe	12-69	100	50(6)	21(9)	68(6)	28(6)
America	119-231	111	50(5)	20(7)	52(6)	28(8)
Asia	161-283	115	54(3)	22(2)	50(2)	47(3)
Average/ totals	**411**		**52(2)**	**20(2)**	**55(2)**	**41(3)**

*Range in number of observations across NUE indices.
**See Table 1 for definitions of each term; Value in parentheses is relative standard error of the mean (SEM/mean*100).

As mentioned earlier, measured NUE in production fields is often less than from research plots such as those summarized in Table 6. An example offered by Cassman *et al.* (2002) was that average RE for fertilizer N applied by rice farmers in the major rice producing regions of four Asian countries was 0.31 (179 farms) compared to 0.40 for field-specific management (112 farms) and 0.50-0.80 in well-managed field experiments. Balasubramanian *et al.* (2004) reported RE for N in cereals of 0.17-0.33 under current farming practices, 0.25-0.49 in research plots, and 0.55-0.96 as a maximum of research plots. In India, RE averaged 0.18 across 23 farms for wheat grown under poor weather conditions, but 0.49 across 21 farms when grown under good weather conditions (Cassman *et al.*, 2002).

Whether trials are in farmer fields or on experiment stations, high-yield cereal systems tend to have higher AE than systems at lower yield levels. This should not be surprising since the higher nutrient requirements of crops at high yield levels are likely to exceed the nutrient supplying ability of soils without the application of fertilizers to a greater extent than at lower yield levels. This increases the difference between the yield of the crop with the application of fertilizers and the yield of the crop without the application of fertilizers. Additionally, a crop with a faster nutrient accumulation rate may reduce the potential for nutrient losses from the production field. In the dataset shown in Figure 3, which is composed of diverse summaries of cereal NUE from around the world, approximately one-third of the variability in AE for N could be explained
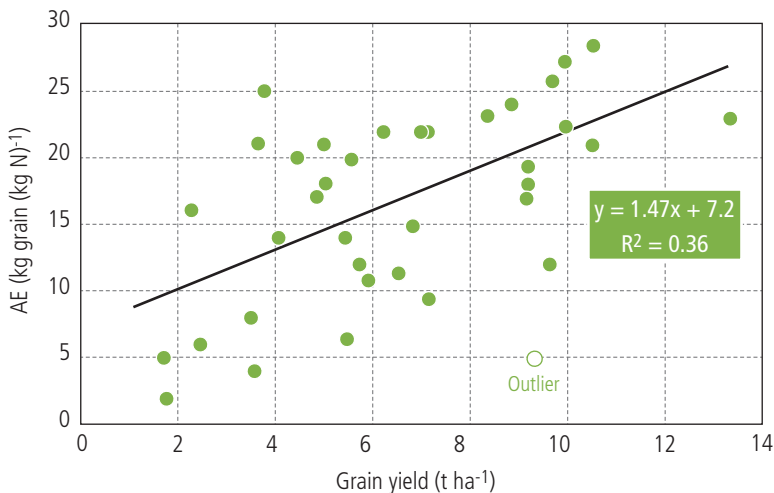
Figure 3. Influence of yield level of the fertilized treatment on typical AE for N reported in NUE summaries of farm and experiment station trials (n=37; data sources: Dobermann, 2007; Ladha *et al.*, 2005; Lester *et al.*, 2010; Liu *et al.*, 2011; Iowa State U. Agronomy Extension, 2011; Norton, R.M., Based on data from Long term NxP experiment in Australia – Dahlen, personal communication. 2011.; Singh *et al.*, 2007).

simply by average grain yield. Yield variation in the dataset was due to a multitude of factors including climate, cropping system, soil properties and system management.

Trends in NUE for N

The considerable variability existing in NUE across regions and cropping systems manifests itself in temporal trends as well. Countries with intensive agriculture—such as US, Germany, UK, and Japan—generally show increasing NUE as a result of stagnant or even decreasing N use and increasing crop yields (Dobermann and Cassman, 2005). However, cropping systems within these countries can vary greatly in temporal trends.

Understanding the whole-system context of NUE trends is critical to proper interpretation of these trends. Comparing PFP trends for N for maize and wheat in the US illustrates this point (Figure 4). Maize PFP increased approximately 50% from 1975 to 2005 while wheat PFP decreased 30% during this same time period, but then increased 30% from 2005 to 2010. The increase in maize PFP resulted mostly from
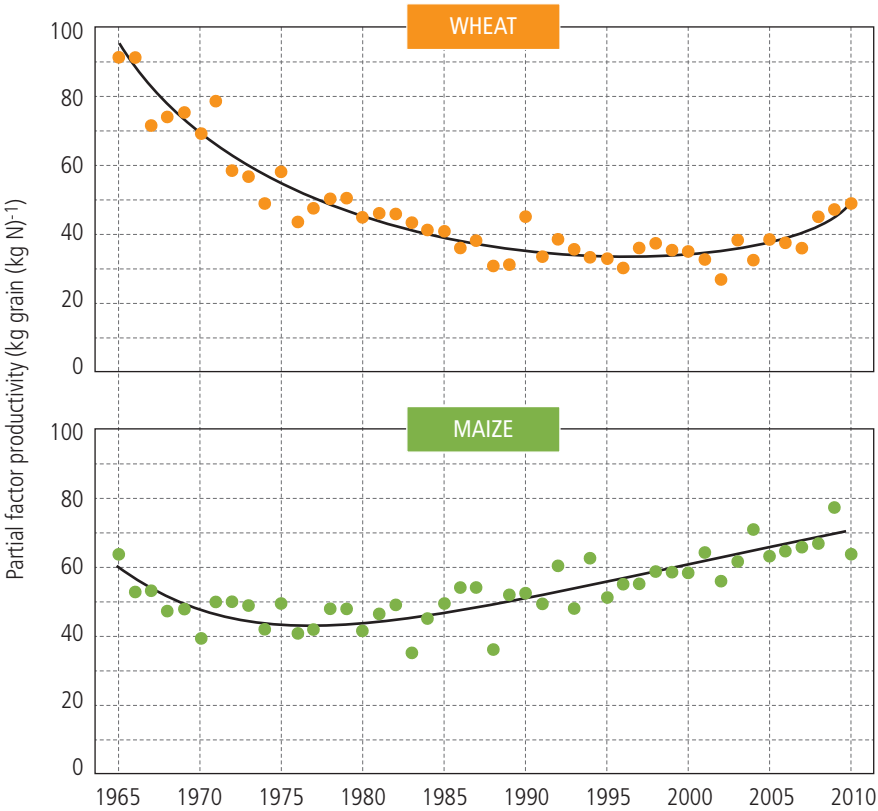
Figure 4. Partial factor productivity in the US for fertilizer N used on maize and wheat from 1965 to 2010 (adapted from USDA-ERS and USDA-NASS, 2011).

improved genetics and crop, soil and nutrient management, which boosted yields by over 80% during this 30-year period. The net effect has been a linear increase in PFP for the last 25 years at a rate of 0.9 kg grain (kg N)$^{-1}$.

So, in the same country where growers had the same access to technology and innovation, why did wheat production not show a similar trend? The answer likely lies in differences between the dominant maize and wheat regions in cropping, tillage and fertilizer application histories. The dominant wheat region has been undergoing a transition from management systems where the dominant N source was the tillage and fallow-induced mineralization of soil organic matter to a less tilled, more intensively cropped system that conserves or builds soil organic matter (Clay *et al.*, 2012). During this transition, wheat production became more dependent on fertilizer as an N source because of the reduction in mining of soil organic N, reducing apparent PFP and PNB (closer to 1). Comparison of PNB between Illinois (a maize-dominant state) and Montana (a wheat dominant state) shows unsustainably high N balances in the past for Montana which have been declining for the past 20 years, while Illinois had potential for closing the gap in the N balance (Table 7). More recently, the PFP trend for wheat has reversed due likely to the same factors that have been increasing PFP for maize systems (Figure 4).

Table 7. Partial nutrient balance for N in Illinois and Montana from 1987 to 2007 (IPNI, 2012a).

State	Dominant cropping system	Partial nutrient balance by year*				
		1987	1992	1997	2002	2007
Illinois	Maize-soybean	0.71	0.76	0.76	0.86	0.87
Montana	Wheat	1.35	1.33	1.00	1.04	1.01

*(Removal by harvest) (Fertilizer N + Recovered manure N + biological N fixation)$^{-1}$

In countries where agriculture is in general undergoing intensification, PFP often shows decreasing trends because fertilizer N use increases at a faster rate than crop yields, though yields are also increasing (diminishing returns). Such is the case for wheat and maize in Argentina (Figure 5). As in the above case for wheat in the US, such declines in PFP are often accompanied with more sustainable PNB relationships where less mining of soil nutrients is occurring. If biological N fixation is not included in the N balances, such shifts can be misleading if the frequency of legumes in the rotation changes over time.

Developing a picture of regional trends in NUE around the world requires a systematic approach where all regions are estimated using a consistent protocol over time. We used that approach in developing Figures 6 and 7 for N and Figures 11 to 14 for P and K. The figures show NUE trends from 1983 to 2007 with each point representing the average of a 5-year period. Data availability (FAO, 2012; IFA, 2012) limited the indicators estimated to PFP and PNB. For nutrient inputs, only mineral fertilizer consumption was considered, excluding nutrients in livestock manure, atmospheric deposition,
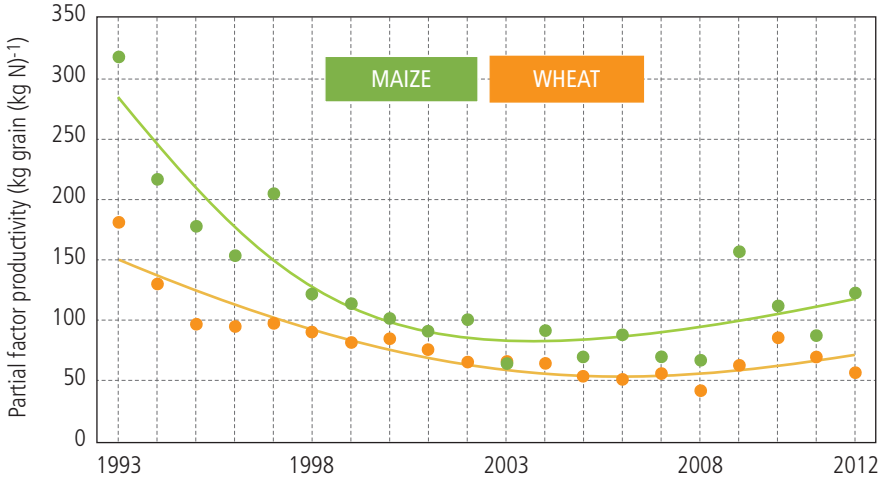
Figure 5. Partial factor productivity in Argentina for fertilizer N used on maize and wheat from 1993 to 2011 (adapted from Garcia and Salvagiotti, 2009).

biological N fixation, and municipal wastes. The crops included from the FAO database were 38 fruits and vegetables, 9 cereals, 9 oil crops, 6 pulse crops, 5 root or tuber crops, and 5 other crops. The major category not included was forage crops that included crops such as silage maize, alfalfa and other hay. This category can be a large source of productivity and nutrient removal in regions where significant confinement livestock operations exist. For example, in the US alfalfa and "other hay" account for over 15% of the total national P removal and over 40% of the K removal (PPI/PPIC/FAR, 2002). However, a proportion of the nutrients contained in forage crops will be returned to the fields as animal manure, but since both forage crops as output and manure as input are excluded from these NUE estimates, the error introduced should in most cases not be large at this broad regional scale. Since biological N fixation was not included for the input estimate, N removal by legumes was also not included for calculating PNB. This may skew regions with more legumes in the rotation towards higher PNB estimates. The nutrient concentration of harvested crops was based on literature values or research trial data (J. Kuesters (Yara), personal communication, 2012).

World PFP and PNB levels have shown a very slight increase over this 25-year period. Regional temporal trends in PFP for N are, in most cases, similar to PNB but trends among global regions clearly differ (Figures 6 and 7). Africa and Latin America in 1985 had by far the highest PFP and PNB values but with trends in opposite directions. The PFP data show that both these regions have extremely high productivity per unit of fertilizer N applied. However, the excessive PNB values for Africa show that it is becoming more dependent on non-fertilizer sources to balance crop removal of N, a precarious and unsustainable situation. In contrast, Latin America has maintained very
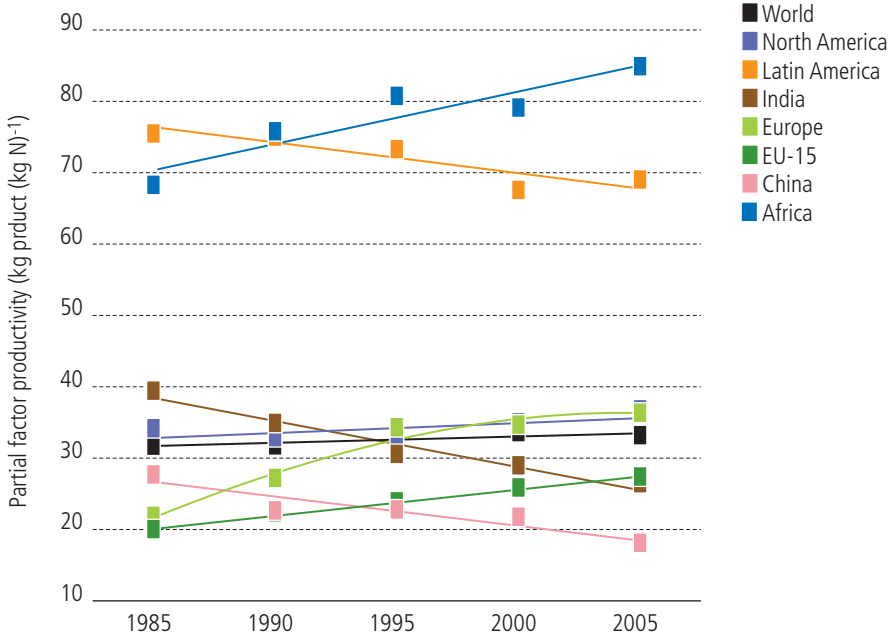
Figure 6. Partial factor productivity for N in global regions, 1983-2007.
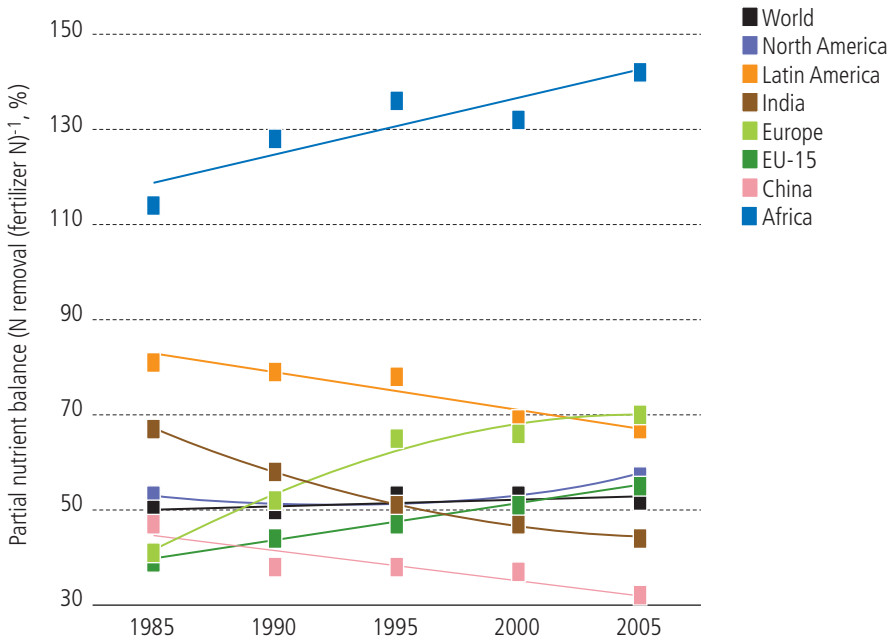
Figure 7. Partial nutrient balance for N in global regions, 1983-2007.

high productivity per unit of N but has also moved towards a more sustainable nutrient balance.

In general, PNB and PFP for Africa, North America, Europe, and the EU-15 are trending upwards, while Latin America, India, and China are trending downwards. It is interesting to note that PNB for Europe during the last decade appears to have leveled off at around 70%, and that PNB for Latin America, India, and China has been declining at about the same rate for the 25-year period.

Trends in NUE for P and K

The major effects of soil properties and typically large legacy effects of previous management dominate NUE relationships for P and K. While most of the benefit and recovery of N addition occur during the year of application, much of the benefit of P and K application on many soils occurs in subsequent years due to effects on soil fertility (Syers *et al.*, 2008). Appropriate evaluation of the current status and long-term trends of NUE for P and K needs to consider these residual effects. Short-term AE, RE and PFP for P and K are usually best interpreted within the context of current soil fertility status and associated PNB which indicates future soil fertility status if the current PNB remains unchanged.

Efficiency measures are greatly influenced by nutrient rate applied and by soil fertility. The P data summarized in Figure 8 are from research conducted in farmer fields in the Southern Cone of South America. Available P in all fields tested was lower than critical values so that a profitable response to P was expected. Agronomic efficiency was highest
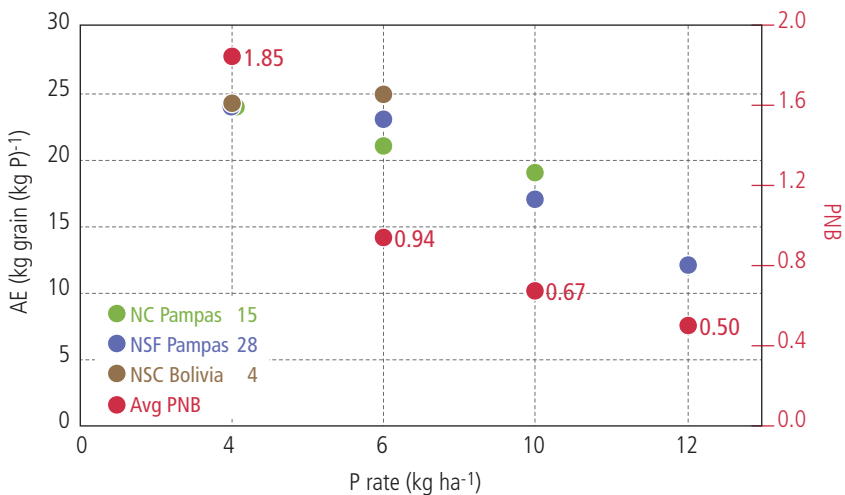
Figure 8. Influence of P rate on agronomic efficiency and partial nutrient balance of soybean in the Southern Cone of South America (adapted from Ferrari *et al.*, 2005; H. Fontanetto, pers. comm.; and Terrazas *et al.*, 2011). Numbers for each group in the legend indicate the number of field trials (n)
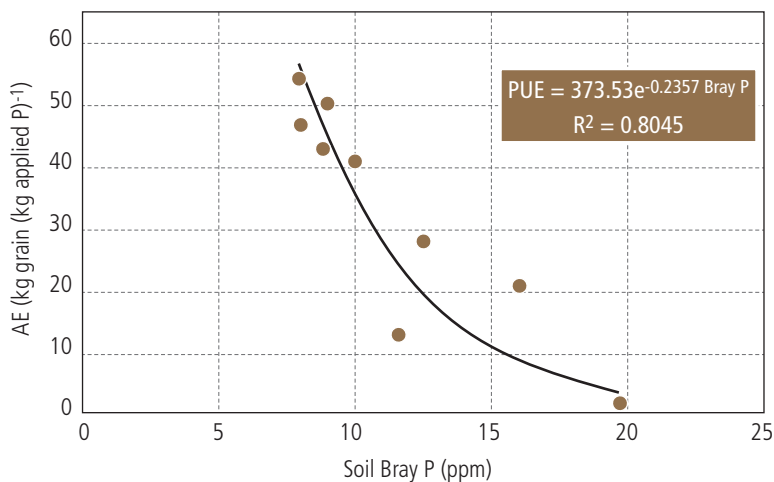
Figure 9. Influence of soil fertility on agronomic efficiency of P fertilizer in wheat experiments in Argentina (Garcia, 2004).

at low rates of P with the lowest rate (10 kg ha^{-1}) being common for soybean-based cropping systems of the region. This rate resulted in an average PNB of 1.85 where soil P levels would be depleted over time – a non-sustainable situation, but better than no fertilizer P at all. The higher rates generated somewhat lower AE values but had PNB values less than one where soil P would be maintained or increased with time. These data illustrate the value in considering multiple NUE indicators when assessing P management.

The effect of soil P fertility on AE and RE is illustrated by wheat experiments from Argentina (Figure 9). Very high AE and RE are measured when soil fertility is well below critical levels and rapidly decline as soil fertility increases. Sustainability is associated with the intermediate AE and RE values observed when rates applied are close to removal, and soil fertility levels are maintained near the critical level.

First year RE in field trials across Asia indicates P recoveries near 25% are typical in that region when fertilizer P is applied at recommended rates (Table 8). These studies were mostly on soils with low P fixation potential and were under favorable climate and management conditions. Dobermann (2007) pointed out that though the average RE values were similar across studies, within-studies RE varied widely from zero to nearly 100%, but that 50% of all data fell in the 10 to 35% RE range. Such variability is to be expected due to the soil fertility and the effects of application rate of fertilizers discussed above.

Regional aggregate data can be used to evaluate the current status of P use and its impact on temporal trends of soil fertility and to test the assumption that P balance impacts soil fertility. Soil tests conducted for the 2005 and 2010 crops in North America by private and public soil-testing laboratories were summarized by IPNI. In Figure 10, the change in median soil P levels for the 12 Corn Belt states over this 5-year period is plotted against the PNB for this same time period. Values of PNB above 0.94 resulted

Table 8. Average RE of P and K from mineral fertilizers in field trials with rice, wheat and maize in Asia. Values shown refer to recommended fertilizer rates or in the case of rice, those that were currently being applied by farmers (Dobermann, 2007; Liu *et al.*, 2006).

Crop, region or management	Number of field trials	Time period	P RE (%)	K RE (%)
*Rice in Asia; farmer's practice	179	1997-1998	24	38
*Rice in Asia; site-specific management	179	1997-1998	25	44
Wheat in India	22	1970-1998	27	51
Wheat in China	744	1985-1995	22	47
Maize in China	592	1985-1995	24	44

*China, India, Indonesia, Philippines, Thailand, and Vietnam.

in declining soil P levels with substantial declines measured for the states with the most negative P balance. These data suggest that long-term PNB is a reasonably good indicator of the future direction of soil P fertility on non-P fixing soils. These relationships would likely differ for low P Oxisols and Andisols that typically have a high capacity to sorb or "fix" applied P; in these soils, a considerably lower PNB would be needed initially to

Figure contents: Y = -18.99x + 17.8, R^2 = 0.86, PNB of 0.935 = 0 change in soil P. Axis labels: Change in median P (ppm) versus PNB*. * NuGIS 1/12/2012; P use includes fertilizer and recoverable manure P
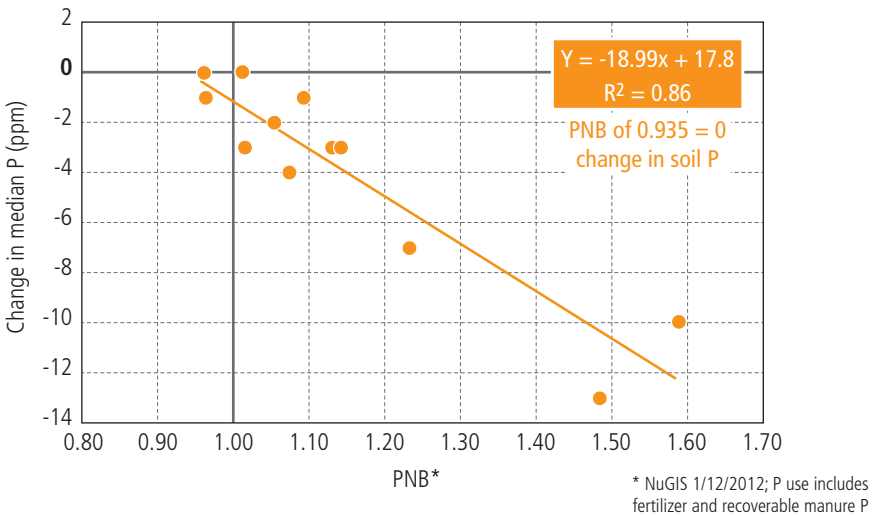
Figure 10. Change in median soil P level for 12 US Corn Belt states as related to state PNB, 2005-2009 (updated from Fixen *et al.*, 2010).

build soil P fertility until high affinity sorption sites are satisfied. Soils with large amounts of free calcium carbonate where precipitation reactions control P in solution, such as those in southern Australia, would also be exceptions where fertilizer P effectiveness in building soil fertility would remain low (McLaughlin, 2012).

The same approach used for N in developing a picture of regional trends in NUE around the world was used for P (Figures 11 and 12). As with N, world PFP and PNB for P have increased over this 25-year period with PFP in the last 5-year period (2003-2007) approaching 195 kg production per kg P and PNB approaching 70%. Regionally, Africa has markedly separated itself from all other regions in terms of both PFP and PNB. In the 1983-1987 period, Africa, India and China had nearly identical PNB levels for P of around 90%, but moved in opposite directions over the 25-year period with PNB in Africa doubling to over 180% while in China and India it dropped to approximately 50%. The PNB value for Africa indicates extreme mining of soil P while the values in China and India indicate that soil P levels should be increasing. These values do not take into account changes in the use of local rock phosphate but there is no evidence that this was significant. There is a paucity of reliable information on the use of rock phosphate as a direct application fertilizer in Africa, but various sources indicate that amounts used have remained very low. Average application rates at the country level are less than 0.5 kg ha^{-1}, even for countries with the highest application rates, indicating insignificant P contribution from rock phosphate sources.

Figure 11. Partial factor productivity for P in global regions, 1983-2007.
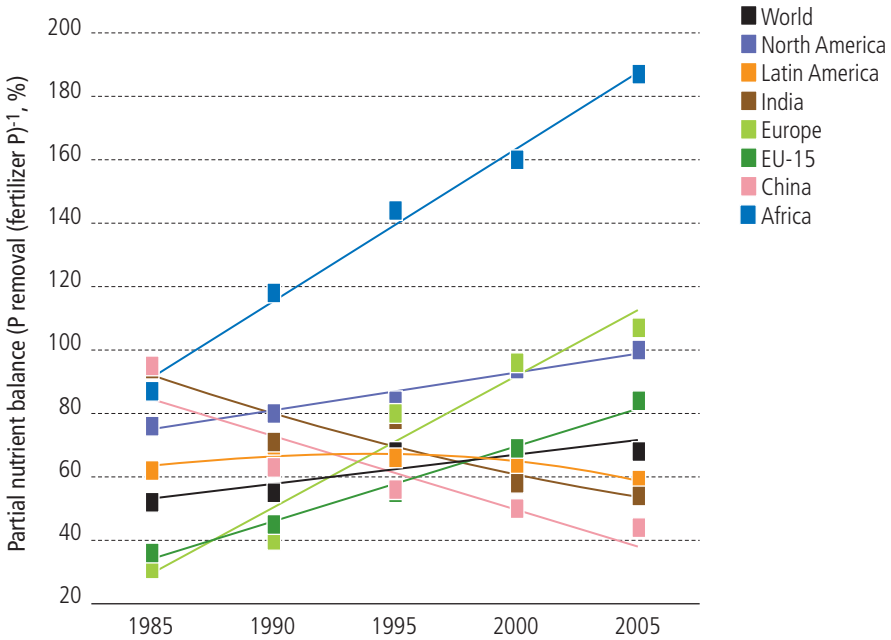
Figure 12. Partial nutrient balance for P in global regions, 1983-2007.

In general, PNB and PFP for Africa, North America, Europe, and EU15 are trending upwards in P, while Latin America, India, and China are trending downwards, just as was the case for N. The absence of manure inputs in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

Information on K use efficiency is more limited than either N or P. This is partly due to the environmentally benign nature of K where interest in efficiency is driven primarily by agronomic or economic factors. The result is less support for research and education on efficient use. The first year recovery efficiency for K is generally believed to be higher than for P with the exception of some strongly fixing clay soils. The first year recovery of applied K has been reported in the range of 20 to 60% (Baligar and Bennet, 1986). Dobermann (2007) summarized average recovery efficiencies in field trials in Asia conducted prior to 1998 showing a range of 38 to 51% (Table 8). Jin (2012) summarized field trials on cereal crops in China, conducted from 2002 to 2006 using an omission plot design, and showed RE for K in the 25 to 32% range and average AE values of 8 to 12 (Table 4). In a more recent set of field trials on winter wheat in North-Central China, RE values for K were somewhat higher in the 34 to 44% range but AE values were again in the 8 to 10 range (Table 9; He *et al.*, 2012). The researchers indicated that

Table 9. NUE of K from mineral fertilizers in three field trials with winter wheat in North-Central China. Average of 2007-2009 (He *et al.*, 2012).

Province	Average rate (kg K ha^{-1})	RE (%)	AE (kg kg K^{-1})
Hebei	81	43	10.2
Shandong	75	44	9.9
Shanxi	100	34	8.1

the lower AE was likely due to K application rates exceeding the optimum for the soil K supply of individual site-years. Dobermann (2007) suggested that AE levels for K of 10-20 were realistic targets for cereals on soils that do not have high available K reserves.

The same approach used for N and P in developing a picture of regional trends in NUE around the world was used for K (Figures 13 and 14). As with N and P, world PFP and PNB for K have increased over this 25-year period, with PFP in the last 5-year period (2003-2007) approaching 145 kg of production kg^{-1} K and PNB approaching 140%. Globally, non-forage crops were removing 40% more K than was being applied as commercial fertilizer during this 5-year period. Regionally, across the 25-year period China underwent the greatest change in PNB, from removing more than 5 times as much K as was being applied to a PNB approaching 100% where K removal and fertilizer
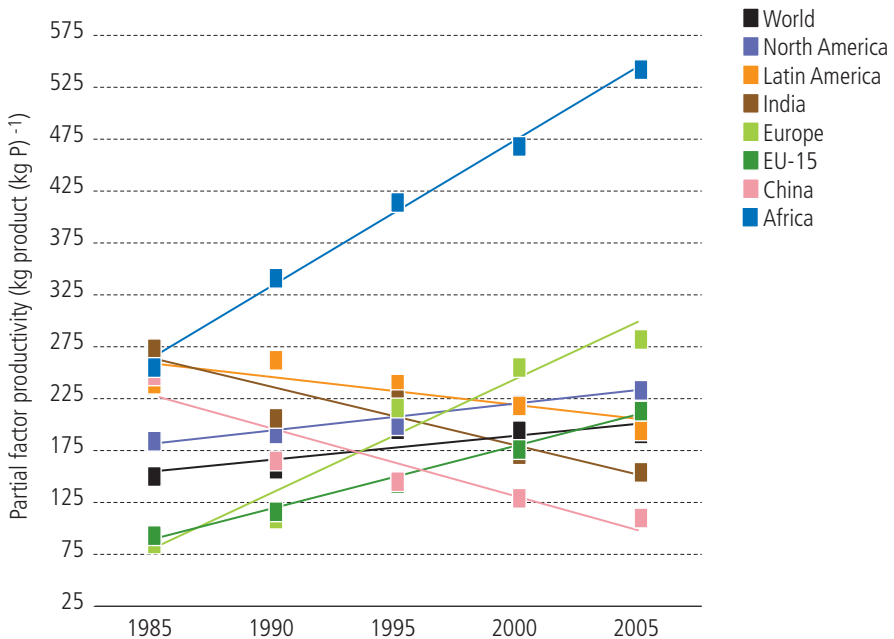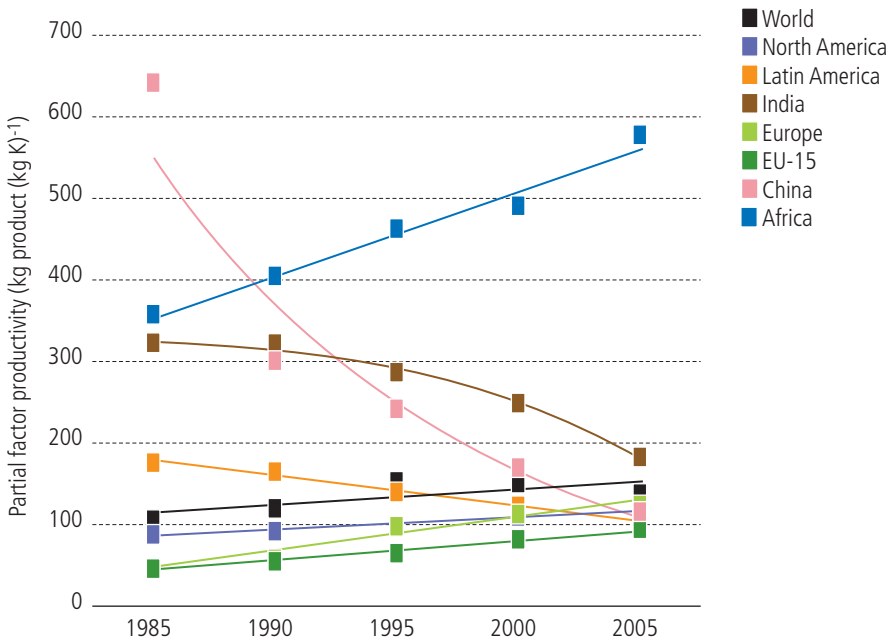

Figure 13. Partial factor productivity for K in global regions, 1983-2007.
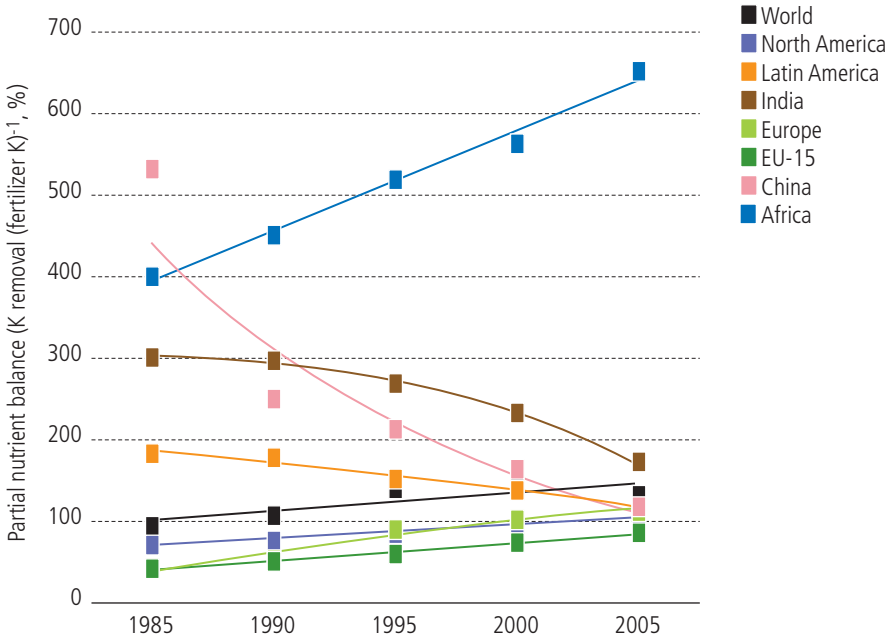
Figure 14. Partial nutrient balance for K in global regions, 1983-2007.

K application are equal. For Africa, both PFP and PNB increased markedly across the 25 years with a PNB in 2003-2007 indicating that crops removed more than six times the amount of K that was applied as fertilizer.

In general, PNB and PFP for Africa, North America, Europe, and EU-15 are trending upwards in K, while Latin America, India, and China are trending downwards, just as was the case for N and P. The absence of forage crop production and K removal in these NUE estimates impacts some regions much more than others and should be kept in mind in comparing the absolute values of the expressions. Differences in temporal trends (slopes of the lines) are likely to be more reliable.

NUE, water and a look forward

Numerous management and environmental factors interact to influence NUE including plant water status. Similarly, plant nutrient status can markedly influence water use efficiency (WUE). The rest of this book will explore the interaction between these two critical crop growth factors. WUE can be improved through nutrient management (Hatfield *et al.*, 2001) although in arid environments it can be important to balance preanthesis and postanthesis growth to ensure adequate water remains to fill grain (van Herwaarden *et al.*, 1998). Nutrient availability affects aboveground biomass, canopy cover to reduce soil evaporation, plant residue production, nutrient dynamics in soil, and thereby improves crop growth and WUE (Maskina *et al.*, 1993; Halvorson *et al.*,

1999; Norton and Wachsmann, 2006). Adequate nutrient supply has shown to improve WUE in several crops (Smika *et al.*, 1965; Corak *et al.*, 1991; Campbell *et al.*, 1992; Varvel, 1994; Payne *et al.*, 1995; Davis and Quick, 1998; Correndo *et al.*, 2012).

Data from a lysimeter experiment conducted in Canada on spring wheat offers an excellent example of the relationship between NUE measures and WUE across a range of N levels (Figure 15). The study included both rainfed (dry) and irrigated (irr) treatments and shows the tremendous impact water status can have on yield response to N and the resulting AE and PNB. The lower graph in the figure shows that a water deficit markedly reduced both AE and PNB at all N levels, but that the efficiency reduction was considerably greater at the lower N levels. The upper graph in Figure 15 shows
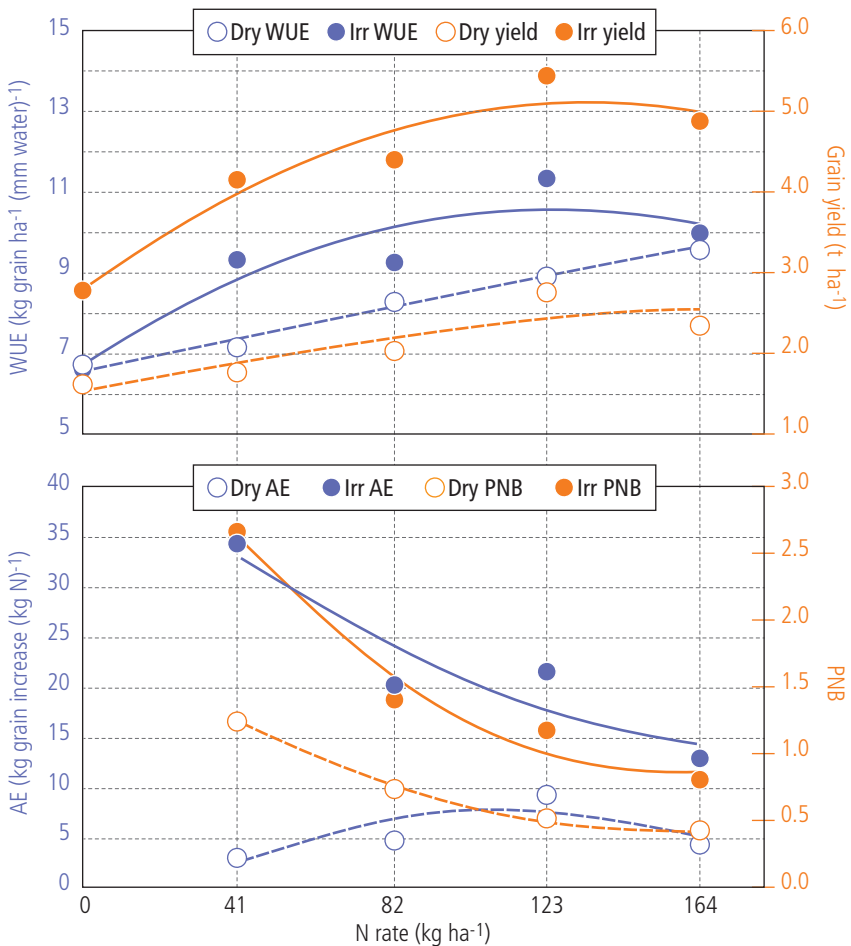
Figure 15. Influence of water status and N application on spring wheat yield and water and N use efficiency in a lysimeter experiment in Saskatchewan, Canada (adapted from Kröbel *et al.*, 2011 and Kröbel *et al.*, 2012, based on original data from Campbell *et al.*, 1977a,b).

improvement in WUE as N levels increase for both the dryland and irrigated treatments. The lower apparent optimum N level for both yield and WUE for the irrigated treatment reflects higher NUE under irrigation shown in the bottom graph.

We draw this chapter to a close reinforcing a point made earlier – that the objective of nutrient use is to increase the overall performance of cropping systems. The data in Figure 15 illustrate that even though NUE generally decreased as N rates increased, the simultaneous increase in WUE and yield until an optimum N rate was attained improved overall system performance. Efficient and effective use of either water or crop nutrients requires that both be managed at optimum levels for the specific system.

Continuous improvement in system performance is a fundamental objective in sustainable intensification. Such improvement is the product of management changes made by individual farmers for individual fields. Numerous efficiency and productivity enhancing nutrient management technologies and practices exist today and are described elsewhere in this book, but many are underutilized. Looking forward, locally defined guidelines for NUE indices that are specific for nutrients, soils, and cropping systems and that can be readily determined by farmers are needed. Such guidelines would help farmers identify what to measure and where improvement is most needed and may be easiest to advance. Guidelines would help define the need for and impact of changes in management on system performance.

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Chapter 3

Water use efficiency in agriculture: Measurement, current situation and trends

Bharat Sharma[1], David Molden[2] and Simon Cook[3]

Abstract

Agriculture is the largest consumer of water and total evapotranspiration from global agricultural land could double in next 50 years if trends in food consumption and current practices of production continue. There is an imminent need to improve the water use efficiency or more importantly the water productivity. This chapter explains in detail the concept and measurement of 'water-use efficiency' and 'water productivity' as applied at plant, field, farm, region/sub-basin, basin and national level through traditional and remote sensing based estimations. Further, the methods for improving water productivity under irrigated, water scarce conditions, paddy fields and large river basins are discussed. The discourse has a special focus towards better understanding and employing the water-nutrient interactions for improving water productivity at all levels. The complexities of measurement and strategies for improvement of physical or economic water productivity increase as the domain of interest moves from crop-plant to field, farm, system, basin, region and national level. Achieving synchrony between nutrient supply and crop demand without excess or deficiency under various moisture regimes is the key to optimizing trade-offs amongst yield, profit and environmental protection in both large-scale commercial systems in developed countries and small-scale systems in the developing countries. Appropriate water accounting procedures need to be put in place to identify the opportunities for water savings. As pressure on the available land and water increases, higher water productivity is the only solution to providing the food that will be needed with the water that is available.

"It is not the quantity of water applied to a crop, it is the quantity of intelligence applied which determines the result - there is more due to intelligence than water in every case."
Alfred Deakin, 1890.

[1] International Water Management Institute (IWMI), New Delhi, India, b.sharma@cgiar.org
[2] International Centre for Integrated Mountain Development, Kathmandu, Nepal, dmolden@icimod.org
[3] International Water Management Institute (IWMI), Colombo, Sri Lanka, s.cook@cgiar.org

Introduction

Improving *water use efficiency* or enhancing *agricultural water productivity* is a critical response to growing water scarcity, including the need to leave enough water in rivers and lakes to sustain ecosystems and to meet the growing demands of cities and industries. Originally, crop physiologists defined water use efficiency as the amount of carbon assimilated and crop yield per unit of transpiration (Viets, 1962) and then later as the amount of biomass or marketable yield per unit of evapotranspiration. Irrigation scientists and engineers have used the term *water (irrigation) use efficiency* to describe how effectively water is delivered to crops and to indicate the amount of water wasted at plot, farm, command, or system level and defined it as "the ratio of irrigation water transpired by the crops of an irrigation farm or project during their growth period to the water diverted from a river or other natural source into the farm or project canal or canals during the same period of time (Israelsen, 1932). This approach was further improved by introducing the concepts of uniformity, adequacy, and sagacity of irrigation (Solomon, 1984; Whittlesey *et al.*, 1986; Solomon and Burt, 1997). Some scholars have even pointed out that the commonly described relationship between water (input, mm or ML) and agricultural product (output, kg or ton) is an *index, and not efficiency* (Skewes, 1997; Barrett Purcell & Associates, 1999). Still this concept of water use efficiency provides only a partial view because it does not indicate the total benefits produced, nor does it specify that water lost by irrigation is often reused by other users (Seckler *et al.*, 2003). The current focus of *water productivity* has evolved to include the benefits and costs of water used for agriculture in terrestrial and aquatic ecosystems. So, *agricultural water productivity* is the ratio of the net benefits from crop, forestry, fishery, livestock and mixed agricultural systems to the amount of water used to produce those benefits (Molden and Oweis, 2007). In its broadest sense, it reflects the objectives of producing more food, income, livelihood and ecological benefits at less social and environmental cost per unit of water consumed. *Physical water productivity* is defined as the ratio of agricultural output to the amount of water consumed, and *economic water productivity* is defined as the value derived per unit of water used, and this has also been used to relate water use in agriculture to nutrition, jobs, welfare and the environment.

Increasing water productivity is particularly appropriate where water is scarce and one needs to realize the full benefits of other production inputs, viz., fertilizers, high- quality seeds, tillage and land formation, and the labor, energy and machinery. Additional reasons to improve agricultural water productivity include (Molden *et al.*, 2010) (i) meeting the rising demands for food and changing diet patterns of a growing, wealthier and increasingly urbanized population, (ii) responding to pressures to reallocate water from agriculture to cities and industries and ensuring water is available for environmental uses and climate change adaptation, and (iii) contributing to poverty reduction and economic growth of poor farmers. Productive use of water means better food and nutrition for families, more income and productive employment. Targeting high water productivity can reduce cost of cultivation of crops and lower energy requirements for water withdrawal. This also reduces the need for additional land and

water resources in irrigated and rain-fed systems. With no gains in water productivity, average annual agricultural evapotranspiration could double in the next 50 years (de Fraiture *et al.*, 2007). Better understanding, measurement and improvement of water productivity thus constitute a strategic response to growing water scarcity, optimization of other production inputs, and enhanced farm incomes and livelihoods.

Measurement of water use efficiency and water productivity

Crop scientists express and measure water use efficiency as the ratio of total biomass or grain yield to water supply or evapotranspiration or transpiration on a daily or seasonal basis (Sinclair *et al.*, 1984). Biomass yield versus evapotranspiration relations have intercepts on the evapotranspiration axis, which are taken to represent direct evaporation from the soil (Hanks, 1974), and yield can be considered a linear function of transpiration, provided water use efficiency does not vary greatly during the season. Linearity of the yield versus evapotranspiration relation denotes that water use efficiency would increase with increase in evapotranspiration as a consequence of increased transpiration/evapotranspiration ratio because the intercept has a constant value. For this reason, water use efficiency also increases with increase in crop water supply up to a certain point (Gajri *et al.*, 1993). Water supply has also been observed to increase fertilizer use efficiency by increasing the availability of applied nutrients, and water and nutrients exhibit interactions in respect of yield and yield components (Prihar *et al.*, 1985; Eck, 1988; Fischer, 1998).

The irrigation system perspective of water use efficiency depends upon the water accounting where losses occur at each stage as water moves from the reservoir (storage losses), conveyed and delivered at the farm gate (conveyance losses), applied to the farm (distribution losses), stored in the soil (application losses) and finally consumed by the crops (crop management losses) for crop production. Depending upon the area of interest, it is possible to measure the water conveyance efficiency, application efficiency, water input efficiency, irrigation water use efficiency and crop water use efficiency (Barrett Purcell & Associates, 1999). Whereas crop water use efficiency compares an output from the system (such as yield or economic return) to crop evapotranspiration the irrigation efficiency often compares an output or amount of water retained in the root zone to an input such as some measure of water applied. The term *'water productivity'* was an attempt to mediate the prevailing complexity and other inherent limitations of the existing concept.

The concept of water productivity (WP) was offered by Kijne *et al.* (2003) as a robust measure of the ability of agricultural systems to convert water into food. So, the basic expression of agricultural water productivity is a measure of output of a given system in relation to the water it consumes, and may be measured for the whole system or parts of it, defined in time and space (Cook *et al.*, 2006).

$$\text{Water productivity} = \frac{\text{Agricultural benefit}}{\text{Water use}}$$

It is normal to represent water productivity in units of kg m^{-3}, where crop production is measured in kg ha^{-1} and water use is estimated as mm of water applied or received as rainfall, converted to m^3 ha^{-1} (1 mm = 10 m^3 ha^{-1}). Alternatively, it may be represented as food (kcal m^{-3}) or its monetary value ($ m^{-3}).

Agricultural systems are defined by plot, field, sub-basin and basin and the crop(s)/cropping patterns followed at each component level. Water productivity values make better sense when the relative comparisons are made at the component parts of the agricultural system. The time period over which water productivity is estimated is determined by the cycle of agricultural production that drives the system. Normally, this would include at least one complete crop cycle (e.g. rice, wheat, maize, vegetables, etc.) extended over a complete year (rice-wheat, maize-wheat, sugarcane, banana, etc.) to account for productive and non-productive water use. Assessment may be extended over several years to derive estimates of average, minimum or maximum water productivity within each season. Cropping systems provide internal benefits in addition to yield, such as fodder, legumes or soil nutrition, which may significantly influence water productivity in subsequent years. Additionally, the patterns of climate, disease and pest infestation, markets, etc. may induce an estimation error at the time of assessment which may, or may not, be representative of the average situation.

Defining the area for estimation

The first step is to define the boundaries of the system for which WP is to be estimated. This is determined by the definition of production system (field, farm, command area, administrative unit) and the area for which water consumption can be defined (plot, field, sub-basin, watershed or basin). Measurement of partial WP for a single crop at field or plot level is the simplest, and some estimation errors may creep in for representation of a large hydrologic system. This shall be explained in a separate section. In rain-fed areas and areas with shallow groundwater levels, WP will vary spatially according to varying water storage capacities of the soil (Bouman *et al,* 2007) and the definition of a particular production system can be underrepresented or overrepresented within areas having a high or low storage capacity.

Estimating the agricultural production: The numerator

Agricultural biomass or production can be expressed in a range of forms, as yield (kg, Mg, t), or food and energy equivalent (kcal), income ($) or other agreed measures of well-being derived from the agricultural system. This may be expressed as:

$$\text{Output per cropped area} \left(\frac{\$}{\text{ha}}\right) = \frac{\text{Production}}{\text{Irrigated cropped area}}$$

$$\text{Output per unit command} \left(\frac{\$}{\text{ha}}\right) = \frac{\text{Production}}{\text{Command area}}$$

Commonly used forms of agricultural production are given in Table 1.

Table 1. Possible forms of agricultural production used for estimating water productivity (adapted from Cook *et al.,* 2007).

Parameter	Agricultural production
Physical water productivity at field, farm or system level	Yield (kg) of biomass, *or* fruit *or* grain
Economic water productivity at farm level	Gross *or* net value of product, *or* net benefits of production (monetary or energy units)
Economic water productivity at basin scale	Any of the above valuations including those derived from livestock, fishery, agroforestry, pastures and plantations.
Macroeconomic water productivity at regional or national scale	Monetary values of all direct and indirect economic benefits minus the associated costs, for all the uses of water in the domain of interest.

Estimation of WP of a principal crop is simple - estimate the yield (kg, t) and agricultural water use (mm, m³) over an area of interest. For large areas, crop production data may be estimated through random surveys and secondary statistics on crop production.

The economic measure of productivity at field scale is gross margin (GM) for a single product during a single phase of the crop rotation. For areas that contain different production systems and for cross-system comparison a composite measure may be required. The Standardized Gross Value of Production (SGVP) was developed to harmonize the differences in local prices at different locations throughout the world. To obtain SGVP, equivalent yield is calculated based on local prices of the crops grown, compared with the local price of the predominant, locally grown, internationally traded base crop. The second step is to value this equivalent production at world prices. To do this, economists normally use long-term averages of World Bank prices to take care of the distortions caused by year-to-year price fluctuations (Sakthivadivel *et al.*, 1999). For example, if the local price of a commodity (say, pulse crop) is twice the local price of wheat, one may consider the production yield of 2 t ha⁻¹ of pulse crop to be equivalent to 4t ha⁻¹ of wheat. Total production of all crops is then aggregated on the basis of 'wheat equivalent' and the gross value of output is calculated as this quantity of wheat multiplied by the average world market price of wheat.

$$SGVP = \left[\sum_{crop} A_i \, Y_i \, \frac{P_i}{P_b} \right] P_{world}$$

where,
SGVP= Standardized Gross Value of Production
A_i = Area cropped with crop i

Y_i = Yield of crop i
P_i = Local price of crop i
P_b = Local price of base crop
P_{world} = Value of base crop traded at average world market price

However, the full range of economic benefits from agricultural production extends far beyond the simple measure of local production, to include indirect and broader impacts (Hussain *et al.*, 2007) which may include higher employment rates and wages, improved markets for inputs (fertilizers, seeds, machines, chemicals, services) and the outputs (commodities, transport, trade) and a general improvement of the economy and well-being. Multipliers of economy-wide farm/nonfarm multipliers vary widely. Estimates in India suggest a multiplier as low as 1.2 for local schemes and up to about 3 for the country as a whole. Multipliers tend to be larger in developed economies, estimated as high as 6 for Australia (Hill and Tollefeson, 1996). Hussain *et al.* (2007) point out that the most significant measure is of marginal value, which shows the additional value created when water is added or lost when water is not available. The noneconomic benefits of production may be measured through improvements in environmental benefits and services and changes in the Human Development Index (Maxwell, 1999) or the Basic-Needs Index (Davis, 2003).

Estimating the water consumed: The denominator

Water input to a field or an agricultural system is not the same as the water used or depleted for crop production. However, we may work out water use efficiency as output per unit of irrigation supply. Water productivity is estimated from the amount of water directly consumed by the agricultural system (evaporation and transpiration) and not the amount of irrigation water applied or rainfall received (Molden *et al.*, 2003, Molden and Oweis, 2007; Kassam *et al.*, 2007, Molden *et. al.*, 2010). This distinction is increasingly important as we move upscale from field to farm to basin because *water that is taken into the system, but not consumed, is available downstream and hence is excluded from calculation.* At a given scale, this may be estimated through a simple water balance equation or by following the water accounting framework (Molden *et al.*, 2003). At field scale, the key term is evapotranspiration (ET), which may be estimated as:

$$ET = P + I + G \pm Q - \Delta S$$

where, P is precipitation, I is irrigation, G is net groundwater flow, Q is run-on or runoff and ΔS is change in soil water content within the root zone, all measured in millimetres of water. Evapotranspiration of crops is normally estimated from more easily measured climatic variables and the predetermined crop-coefficients (Allen *et al.*, 1998).

Based on the above, two important indicators for 'water applied' and 'water used' will be (Sakthivadivel *et al.*, 1999):

$$\text{Output per unit irrigation supply} \left(\frac{\$}{m^3}\right) = \frac{\text{Production}}{\text{Diverted irrigation supply}}$$

$$\text{Output per unit water consumed} \left(\frac{\$}{m^3}\right) = \frac{\text{Production}}{\text{Volume of water consumed by evapotranspiration}}$$

The relationship between water diversion and depletion is complex, and significant variations exist due to variations in water diverted. The variations average out if one moves out to a larger scale. Interventions should start in areas with the lowest water productivity.

Measuring regional- and basin-level water productivity

At the larger scale of an administrative unit or the sub-basin and basin it is rather impossible to have water balances for each field and the crop. Moreover, at the field or system scales, part of the water delivered is often reused within the field or the system or elsewhere in the basin. To avoid these complications in capturing the reuse and benefits outside the areas of interest, the value of production per unit of crop consumptive water use (CWU) is considered to be a better measure of water productivity (Molden *et al.*, 2003). Consumptive water use in irrigated areas implies the potential evapotranspiration (ET_p), while in rain-fed areas it is the minimum of effective rainfall and ET_p. Depending on the availability of data, resources and competence and the objective of analysis, the estimates of crop yields and the consumptive water use may be made through following either the statistical data on crop yields and historical values of crop coefficients and potential evapotranspiration or the more recent approaches utilizing remote-sensing imagery and crop modelling.

Statistical approach

Long-term (minimum of 3 years) subnational data on detailed land use, crop production, extent of irrigated and rain-fed areas of different crops and the combined total production can help estimate the value of crop production. Climate data (monthly ET_p and rainfall available from IWMI Global Climate and Water Atlas (2001), or FAO and local meteorological departments) and crop coefficients of the major crops can help determine consumptive water use. The method has been described in detail by Amarasinghe *et al.* (2010). The important governing equations are given below:

- Crop water use in irrigated areas (IR) is potential ET during crop growth periods of different seasons and is given by,

$$CWU_{ij}^{IR} = Area_{ij}^{IR} \ x \ \left(\sum_{k\varepsilon} Kc_{jk} \ x \ \left\{ \sum_{I\varepsilon months} ET_{ikl}^{P} \right\} \right)$$

for the jth crop in the ith season (k denotes the specific crop growth stage, and i denotes the month in the growing season of the crop). Kcs are the crop coefficients over the defined growth periods and ET_ps are monthly reference evapotranspiration values.

- CWU in rain-fed areas is only the effective rainfall during the season, and is estimated as:

$$CWU_{ij}^{RF} = Area_{ij}^{RF} \text{ x} \sum_{k\epsilon growth\ periods} min\left(Kc_{jk}\ ET_{jkl}^{p}\ \sum_{l\epsilon months}\ ET_{jkl}^{p}\ \right)$$

where, ERF_{jkl} is the effective rainfall of lth month in the kth growth period.

- CWU of the area of interest (district, zone, etc.) is estimated as:

$$CWU = \sum_{i\epsilon seasons}\ \sum_{j\epsilon crops}\ (CWU_{ij}^{IR} + CWU_{ij}^{RF})$$

- Total WP of the area of interest is estimated by:

$$WP = \frac{\sum_{j\epsilon crops} Average\ yield_j \text{ x } (Area_i^{IR} + Area_j^{RF})}{CWU}$$

Integrating use of remote sensing and crop census data

Lack of data required for monitoring the productivity of land and water resources, especially over vast irrigation schemes and river basins can often hamper the application and understanding of the water productivity framework and design of the interventions. Integration of satellite measurements for the climatic data with ancillary *in-situ* data into a geographic information system shall be quite helpful (Bastiaanssen *et al.*, 2003). Remote-sensing measurements are converted to crop yield and to actual evapotranspiration. Existing land use-land cover maps and census data (with ground truthing) are used to map the dominant crops. The yields are calculated from national statistics and interpolated to pixel level using the Normalized Difference Vegetation Index (NDVI) satellite data. Crop evapotranspiration (ET_a) is mapped using a Simplified Surface Energy Balance (SEBAL) model based on the satellite data of land surface temperature and data from the weather stations (Bastiaanssen *et al.*, 2005). WP of dominant crops and total agricultural yield are mapped by dividing crop yield by ET_a for each pixel (Ahmad *et al.*, 2009; Cai and Sharma, 2010). These methods have now been used extensively to map WP of large sub-basins in Pakistan (Ahmad *et al.*, 2009), the Indo-Gangetic basin (Cai *et al.*, 2010), the Karkheh basin in Iran (Ahmad *et al.*, 2009), the Nile basin (Karimi *et. al.*, 2012) and several others.

These WP maps display the spatial variation in great detail (Figure 1). We can identify well-performing 'bright spots' and low-performing 'hot spots' regardless of administrative boundaries. Linking them to rainfall distribution, topography, groundwater level and other spatial information can indicate causal relationships, which is useful to provide information for improved intervention planning (Sharma *et al.*, 2010).
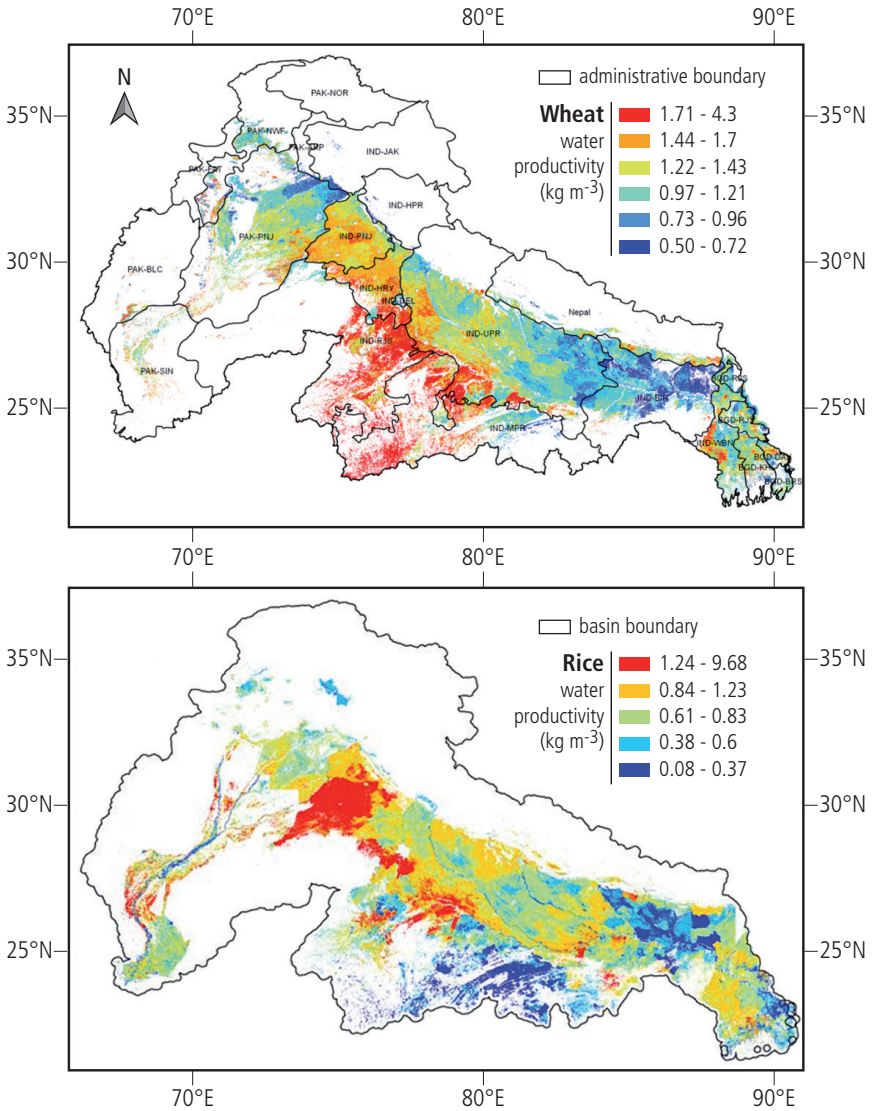
Figure 1. Variations in rice and wheat water productivity in the Indo-Gangetic basin.

Improving agricultural water productivity

Irrigation along with fertilizers and improved seeds has been essential components of a global strategy for increasing agricultural productivity. During the past decades emphasis on improved agricultural water management has been on increasing irrigation water use efficiency, but more recently enhanced emphasis is placed on producing more with relatively less water – increasing water productivity. There is a need to find new ways to increase water productivity by improving biological, economic and environmental output per unit of water used in both irrigated and rain-fed agricultural systems. Physical productivity improvements can be made by obtaining more productive transpiration from rain and irrigation withdrawals, producing more and higher-value crops per unit of transpiration, reducing evaporation, and managing agricultural water deliveries and drainage better. Such opportunities are very diverse and occur at biological, environmental and management levels.

Water productivity at plant level

Actual crop yield and actual evapotranspiration both depend on physiological processes – stomata need to open for carbon inhalation and vapour exhalation. For a given crop variety and climate there is a well-established linear relationship between plant biomass and transpiration (Steduto *et al.*, 2007). Different kinds of plants are more water-efficient in terms of the ratio between biomass and transpiration. C3 crops, such as wheat and barley, are less water-efficient than C4 crops, such as maize and sugarcane. The most water-efficient crops are the CAM (Crassulacean acid metabolism) crops such as cactus and pineapple (xerophytes). One of the most successful strategies of the plant breeders has been to develop varieties with a higher harvest index (ratio of marketable grain yield to total crop biomass), achieving more economic produce per unit of transpiration. This plant-breeding strategy has probably raised the potential for gains in water productivity more than any other agronomic practice over the last 40 years (Keller and Seckler, 2004). The harvest index of wheat and maize improved from about 0.35 before the 1960s to 0.5 in the 1980s (Sayre *et al.*, 1997). This happened during the era of the Green Revolution in Asia and elsewhere. However, it appears that this strategy has achieved its potential and further increase in harvest index has slowed down. New innovations in plant biotechnology like the development of drought-tolerant varieties for arid zones and salt and flood-tolerant rice for the coastal areas are required to make the next breakthrough. Introduction of submergence-tolerant Scuba gene in rice is one such good example (Septiningsih *et. al.,* 2009)

The near linear relationship (in good productive fields) between transpiration and crop production has far-reaching consequences for water needs. Increase in food production in productive areas is achieved with a near proportionate increase in transpired water. Molden *et al.* (2010) identified this as the main reason why increases in food production have caused serious environmental consequences, e.g. steep decline in water tables in the highly productive areas of the Indus basin and elsewhere (Rodell *et al.*, 2009). Feeding more people will require more water to be transpired. An alternative strategy may be to provide higher attention to low productivity areas in Africa and

South Americas where application of small amounts of water and fertilizers can pay much larger dividends (Rockström *et. al.*, 2007, Rockström and Barron, 2007; Sharma *et al.*, 2010).

Water and fertilizer interactions at the field and farm level

Water availability, water use and nutrient supply to plants are closely interacting factors influencing plant growth and yield production. It is generally reported that application of fertilizers enhances water use efficiency by causing greater increase in yield relative to that in evapotranspiration (Viets, 1962; Ritchie, 1983). Evapotranspirational and transpirational water use efficiency can be increased by raising soil nutrient levels. Adequately fertilized soils promote rapid leaf area expansion, thus increasing transpiration, and more rapid ground cover, thus reducing evaporation and increasing evapotranspirational water use efficiency. Raised soil nutrient levels seem to exert additive effects on water use efficiency, and increasing or optimizing yields by adequate application of fertilizers will increase transpiration efficiency of the crop plants (Schmidhalter and Studer, 1998). Plants which have adequately used fertilizers may also show higher drought tolerance (Lahiri, 1980; Wang *et al.*, 2011). Water use efficiency also increases with increase in water supply up to a certain point. Water supply has been observed to increase fertilizer use efficiency by increasing the availability of applied nutrients. In fact, water and nutrients have been shown to exhibit interactions in respect of yield (Prihar *et al.*, 1985; Aggarwal, 2000). Combination effects of nitrogen (N) and irrigation are generally more than the sum of their individual effects. Gajri *et al.* (1993) very conclusively show that in deeply wetted coarse-textured soils with low organic matter, N application and early-post seeding irrigation in wheat enhance profile water use by increasing depth and density of rooting as well as leaf area index and leaf area duration. While better rooting increases capacity of the plant to extract water by increasing the size of the water reservoir, extensive canopy with longer duration increases the plant demand for water. Increased canopy also increases the transpiration component of evapotranspiration. Thus nitrogen application, apart from increasing evapotranspiration and transpiration/evapotranspiration ratios, also increases water use efficiency (Table 2). A strong interaction between N and water for yield, dependence of water use efficiency on nitrogen rate, and nitrogen use efficiency on water supply have important management implications. Similarly, water use efficiency was 119% and 150% higher when only pre-sowing irrigation and pre-sowing irrigation plus phosphorus application were made, respectively, to the wheat crop, as compared to control (Li *et al.*, 2004). Fertilizer rates, over which farmers usually have better control, need to be adjusted properly in relation to the available water supplies.

In several studies, soil nitrogen level was positively related to water use efficiency (Paramweswaran *et al.*, 1981; Heiholdt, 1989). Similarly, applying phosphorus fertilizers increases root density and rooting depth and the amount of water available to plants is increased. Phosphorus, in a balanced soil fertility program, increases water use efficiency and helps crops achieve optimal performance under limited moisture conditions (Payne *et al.*, 1992; Wang *et al.*, 2011). The uptake of water by the plant roots and the transport of the water to other parts of the plant are significantly determined by

Table 2. Nitrogen and irrigation effects on water use efficiency (kg grain ha^{-1} mm^{-1}) and N-use efficiency (kg grain (kg fertilizer N)$^{-1}$) in wheat at Ludhiana, India (adapted from Gajri *et al.*, 1993).

Irrigation (mm)	Water use efficiency				N-use efficiency		
	N rate (kg ha^{-1})				N rate (kg ha^{-1})		
	0	40	80	120	40	80	120
No irrigation (rain-fed)	2.8	4.4	6.3	3.6	5.3	4.8	0.9
50	5.2	9.4	10.3	10.9	23.3	12.0	9.8
120	5.7	8.4	10.3	9.0	23.0	17.6	8.8
300	5.1	7.0	8.6	8.8	19.5	20.0	14.8

potassium. Potash fertilizers are directly involved in the water management of the plant since it reduces water loss through transpiration. In sandy soils, water use efficiency for total dry matter production is increased by potassium application (Schmidhalter and Studer, 1998; Prasad *et al.*, 2000). Based on the results of a number of on-farm trials in the savannahs prone to water scarcity, Rockstrom and Baron (2007) also concluded that crop transpiration and yield relationship show non-linearity under on-farm and low-yield conditions. With integrated soil and water management, focusing on mitigation of dry spells and improved soil fertility can potentially more than double on-farm yields. In most cases, increasing or optimizing yields by the use of adequate fertilizers will increase water use efficiency.

Typically, in situations where yield is less than 40-50% of the potential, non-water factors such as soil fertility, limit yield and crop water productivity. However, when yield levels are above 40-50% of their potential, yield gains come at a near proportionate increase in the amount of evapotranspiration (Figure 2); thus incremental gains in water productivity become smaller as yields become higher. For example, the application of relatively small amounts of water and fertilizers for raising yields from 1 to 2 t ha^{-1} will lead to much higher gains in water productivity than doubling the yields from 4 to 8 t ha^{-1} (Molden *et al.*, 2010).

Thus, there appears to be a considerable scope for improving the productivity relative to evapotranspiration before reaching the upper limit. This variability is due to management practices and is important because it offers hope for possible improvements in the ratio between evapotranspiration and marketable yield. For the high productivity fields, balanced use of fertilizers should be encouraged to ensure sustainable productivity in the intensive cropping system as its lack could lead to significant decline in yields and water use efficiency with lapse of time. Additions of organic materials to soil increases soil water-holding capacity, which in turn improves water availability to plants (Fan *et al.*, 2005).
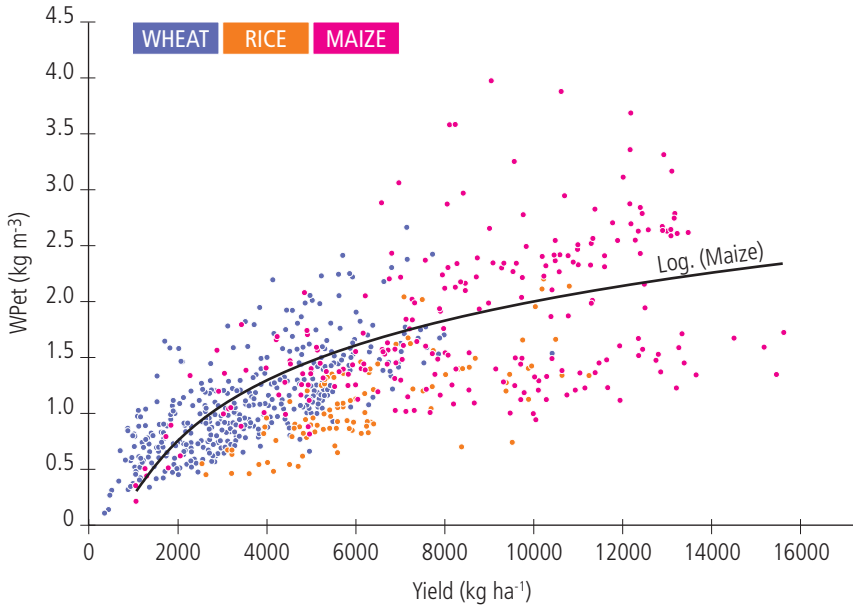
Figure 2. Water productivity gains are higher at lower yield levels and tend to be proportionate at higher yield levels (adapted from Zwart and Bastiaanssen, 2004).

Water productivity under scarce water conditions

Serious water deficits and deteriorating environmental quality are threatening agricultural sustainability in large parts of Asia and Africa. To increase crop yield per unit of water requires both better cultivars and better agronomy. The challenge is to manage the crop or improve its genetic makeup. After analysing a large dataset Passioura (2006) found that in the field, the upper limit of water productivity of well-managed water-limited cereal crops is typically 20 kg ha^{-1} mm^{-1}. If the productivity is markedly less than this (e.g. rain-fed water use efficiency in China is 2.3 kg ha^{-1} mm^{-1}, far less than the potential; Deng *et al.*, 2006), it is likely that major stresses other than water appear, such as poor nutrition and diseases. Unfortunately, there are no genetic transformations that are likely to improve water productivity greatly. Small and timely irrigation, along with management of soil nutrients is the focal issue which is shown to increase water use efficiency by 10-25%. Often, soil fertility is the limiting factor to increased yields in rain-fed agriculture. Soil degradation, through nutrient depletion and loss of organic matter, causes serious yield decline closely related to water determinants, as it affects water availability for crops, due to poor rainfall infiltration, and plant water uptake, due to weak roots. Studies have even shown that within certain limits, nitrogen and water supply have substituted for each other in increasing crop yields (Gajri *et al.*, 1993). In sub-Saharan Africa, soil nutrient mining is particularly severe. By farming intensively without replenishing soil nutrients, farmers across sub-

Saharan Africa have lost nitrogen, phosphorus, and potassium on an average of 22, 2.5 and 15 kg ha^{-1}, respectively, annually over the past 30 years – the yearly equivalent of US$ 4 billion worth of fertilizers. As a result, yields are meagre (IFDC, 2006; Gilbert, 2012). Similarly, in India, participatory watershed management trials in more than 300 villages showed that farming practices had depleted soils not only in macronutrients but also in micronutrients such as zinc and boron, and secondary nutrients such as sulphur beyond the critical limits. A substantial increase in crop yields of 70-120% was achieved when both micronutrients and adequate nitrogen and phosphorus were applied to a number of rain-fed crops (maize, sorghum, beans, pigeon pea, and groundnut) in farmers' fields (Rego *et al.*, 2005). Therefore, investment in soil fertility directly improved water management. The rainwater productivity was increased by 70-100% for maize, groundnut, mung bean, castor and sorghum by adding boron, zinc and sulphur. Even in terms of economic returns, rainwater productivity was substantially higher by 1.50 to 1.75 times (Rego *et al.*, 2005).

The low water use efficiency in farmer's fields compared with well-managed experimental sites indicates that more efforts are needed to transfer water saving technologies to the farmers. Under such scenarios, water-saving agriculture and water-saving irrigation technologies, including deficit irrigation, low pressure irrigation, subsurface drips, drip irrigation under plastic covers, furrow irrigation, rainfall harvesting and conservation agriculture shall be quite helpful. Water-saving agriculture includes farming practices that are able to take full advantage of the natural rainfall and irrigation facilities. Where water is more limiting than land, it is better to maximize yield per unit of water and not yield per unit of land. Limited or deficit irrigation is becoming an accepted strategy in West Asia and North Africa (Table 3; Oweis and Hachum, 2009) and northern China regions. Supplemental irrigation, the combination of dryland farming and limited irrigation, is an ideal choice for improving crop yields in rain-fed regions (Deng *et al.*, 2006). Results from a nationwide study in India showed that water used in supplemental irrigation had the highest marginal productivity and with improved management, an average increase of 50% in total production can be achieved with a single supplemental irrigation. Water harvesting and supplemental irrigation are economically viable even at the national level. Droughts have very mild impacts on productivity when farmers are equipped with supplemental irrigation (Sharma *et*

Table 3. Gains in water productivity for wheat grain under rain-fed and supplemental irrigation with different levels of nitrogen in northern Syria (source: Oweis and Hachum, 2009).

Nitrogen application rate (kg N ha^{-1})	Water productivity (kg grain m^{-3})	
	Rain-fed water	Irrigation water (one supplemental irrigation)
0	0.54	0.81
50	0.89	1.41
100	0.84	2.14
150	0.81	1.40

al., 2010). Increasing the availability of plant nutrients increases yields as well as water use by the crop; however, the increase in water use is usually small – generally < 25% (Power, 1983). A classic example is provided by Carlson *et al.* (1959) who showed that maize yields were doubled primarily by N fertilizers whereas transpiration varied by less than 10%.

On-farm water use efficiency can be further improved by moving to a more efficient irrigation system. Maximum values of water use efficiency and harvest index occur under appropriately controlled water conditions. Micro irrigation has developed rapidly in recent years and adopted for a variety of high-value crops in water-scarce regions. In northwest China, traditional furrow or border (flood) irrigation methods have an annual average water demand of about 7,320 m^3 ha^{-1} in contrast to only 3,250 m^3 ha^{-1} for fields under micro irrigation (Deng *et al.*, 2006). Use of subsurface drip irrigation has also progressed from being a novelty employed by researchers to an accepted method of irrigation of both annual and perennial crops. Analyses of the data for 15 years at Water Management Research Laboratory have demonstrated a significant yield and water use efficiency increase in a number of crops (tomato, cotton, alfalfa, and cantaloupe). The use of high-frequency irrigation resulted in reduced deep percolation and increased use of water from shallow groundwater when crops were grown in high water table areas (Ayars *et al.*, 1999). In the Middle East, wheat yields were twice as high under subsoil irrigation compared with furrow irrigation. Water use efficiency ranged from 1.64 to 3.34 in subsoil irrigation and from 0.46 to 1.2 kg grain m^{-3} in furrow irrigation; and N release from soil was also much higher under subsoil irrigation (11-216 kg N ha^{-1}) than under furrow irrigation (11 to 33 kg N ha^{-1}) (Banedjschafle *et al.*, 2008). Without adequate water, nitrogen use efficiency remains low, resulting in substantial nitrogen losses. Too much water leads to excessive NO_3–N leaching and lower water productivity. The lack of N is a cause of low water productivity but too much of it leads to lower nitrogen use efficiency and higher losses. Though increased NO_3–N leaching is an inevitable by-product of increased WP, its adverse impacts can greatly be reduced by managing the quantity and timing of nitrogen fertilizer and water application (Nangia *et al.*, 2008). Better inorganic nitrogen and water management lead to higher water productivity and, at the same time, less NO_3–N leaching. The use of slow- or controlled-release fertilizers can further mitigate the NO_3–N leaching.

Water productivity under paddy fields

A unique feature of most commonly cultivated irrigated lowland rice culture is crop growth in submerged soil. In transplanted rice, fields are puddled to reduce percolation and are flooded before planting and the daily losses are made up through frequent irrigations. Rice can also be planted by direct seeding, using either wet seeding, with pre-germinated seed broadcast on a puddled soil surface or dry seeding after normal soil tillage with flooding after the seedlings are established. Bhuyian *et al.* (1995) showed that wet-seeded rice culture requiring less water is superior to the traditional transplanted rice in terms of water use efficiency. More recently, aerobic rice, system of rice intensification (SRI) technique and irrigating rice fields with drips and micro sprinklers are also gaining ground. For a typical 100-day season of modern high-

yielding rice, the total water input varies from 700 to 5,300 mm, depending on soil, climate and hydrologic conditions, with 1,000-2,000 mm as a typical value for many lowland areas (Tuong and Bouman, 2003). Water productivity of lowland rice (based on irrigation+rainfall) varies from 0.2 to 1.2 kg m^{-3} and is much less than for wheat (0.8 to 1.6 kg m^{-3}) and maize (1.6 to 3.9 kg m^{-3}). Water productivity of rice may be improved through reducing large amounts of unproductive water outflows during the crop growth and using the rain more efficiently. Instead of keeping the rice field continuously flooded with 5-10 cm of water, the floodwater depth can be decreased, the soil can be kept around saturation or alternate wetting and drying regimes can be imposed. Dry-seeded rice technology offers a significant opportunity for conserving irrigation water by using rainfall more effectively. Studies have shown that maintaining a field bund of 22 cm height around rice fields had helped in capturing more than 95% of seasonal rainfall in paddy fields and thus reduced the need for irrigation (Humphreys *et al.*, 2005). Dry-seeded rice significantly increased water productivity in respect of irrigation over wet-seeded and transplanted rice. Aerobic rice, a new approach to reducing water inputs in rice, is to grow the crop like an irrigated upland crop, such as wheat and maize. With suitable stress-tolerant cultivars, the potential water savings of aerobic rice are large, especially on soils with high percolation rates. On a regional basis, large amounts of irrigation water may be saved by delaying the rice transplanting to avoid the excessively hot summer season. To bring some semblance to the fast-depleting water tables (assigned to large-scale summer paddy cultivation) in Indian Punjab, the government enacted a legislation to force all farmers to delay (from as early as 10th May) transplanting of paddy to 15th of June. Studies have shown that this legislation resulted in real water savings of about 2.18 billion m^3 (7% of annual draft in the state) of water (Sharma and Ambili, 2010).

Studies have also shown that water productivity in rice was significantly increased by N application which increased grain yield through an increased biomass and grain number. In irrigation systems with a shallow water table, optimal N management is as important as water saving irrigation to enhance water productivity. Fischer (1998) estimated that if the technologies that affect nutrient utilization by the rice crop remain unchanged, the production increase will require almost 300% more than the present application rate of N alone in irrigated environments. Achieving synchrony between N supply and crop demand without excess or deficiency under various moisture regimes is the key to optimizing trade-offs amongst yield, profit, and environmental protection in both large-scale systems in developed countries and small-scale systems in developing countries. N fertilizer losses in water-intensive paddy fields are thus a symptom of incongruity between N supply and crop demand rather than a driving force of N efficiency and thus provide significant opportunities by improved management of nitrogen and water resources.

Water productivity of large systems/river basins

At larger regional or river-basin scales with more users, and more interaction between users, water productivity issues become increasingly complex. Minimizing non-productive depletion of water flows, improving management of existing irrigation

facilities and reallocating and co-managing water among uses by allocating water to high-value uses and the outflows for the environment and downstream, are some of the pathways for improving water productivity at the basin level. The primary options to create 'new water' are to transfer the consumptive portion of existing agricultural allocations to other uses, construction of desalination facilities and the creation of additional storage (at the surface or in the aquifers) of surplus floodwaters (Frederiksen and Allen, 2011). At the same time, the common water conservation practices – including urban indoor and outdoor efficiency programs, precision irrigation systems, improvement in soil moisture monitoring and management, deficit irrigation and other approaches – have enormous potential to conserve water in several basins. We must have appropriate water-accounting procedures in place in order to identify the opportunities for water savings. Each basin is different, and therefore the mix of demand- and supply-side solutions will vary according to what is hydrologically, economically, socially and politically possible (Gleick *et al.*, 2011).

A recent assessment of water productivity in ten major river basins across Asia, Africa and South America, representing a range of agro-climatic and socioeconomic conditions showed that there was very high inter-basin and intra-basin variability, attributed mainly to the lack of inputs (including fertilizers), and poor water and crop management (Cai *et al.*, 2011). Intensive farming in the Asian basins (Yellow River, Indus-Ganges, Mekong, and Karkheh) produces much greater agricultural outputs and higher water productivity. Largely subsistence agriculture in African basins (Limpopo,

Table 4. Water productivity of important crops in some major river basins in Asia and Africa (adapted from Cai *et. al.*, 2011).

Basin	Water source	Cropland area (Mha)	Crop types	Yields (t ha^{-1})	Water productivity (kg m^{-3})
Yellow River	irrigated	7.5	wheat	3.7	1.39
			maize	5.3	0.97
			rice	5.4	0.5
Mekong	rain-fed	8.80	maize	3.0	1.09
			soybean	1.40	0.41
	irrigated	3.28	rice	2.87	0.43
			sugarcane	64.5	9.81
			maize	3.79	0.58
Indo-Gangetic	irrigated	62.1	rice	2.6	0.74
			wheat	2.65	0.94
Limpopo	rain-fed	2.06	maize	3.6	0.14
Volta	irrigated	0.036	millet	1.0	0.1
Sao Francisco	irrigated	0.355	maize	1.3	0.15
			sorghum	1.0	0.1
			millet	0.9	0.08

Niger, and Volta) has significantly lower water productivity (Table 4).Yields of the major crops (maize, wheat, rice) vary both across and within basins. All three crops in the Yellow River basin have relatively high yields. The Indus-Ganges basins have the most intensive cultivation, but have relatively low yields overall for both rice and wheat, which are the major sources of food and income.

There is large intra-basin variability in all the basins. The average yield of maize in the Limpopo is 3.6 t ha^{-1}. While the irrigated commercial farms with good inputs of fertilizers and crop management yield as high as 9 t ha^{-1}, the large areas of subsistence farms, which are threatened by frequent droughts and soil nutrient depletion, yield less than 2 t ha^{-1}. The Indian states of Punjab and Haryana, the "bright spots" in the Indus-Ganges basin yield more than double elsewhere (Figure 1). Similarly, variation in water productivity in different basins may be related to the use of fertilizers, crop management and other inputs. Water productivity of maize is highest in the Yellow River (0.97 kg m^{-3}, fertilizer use of > 250 kg ha^{-1}), followed by Mekong (0.58 kg m^{-3}, fertilizer use ~ 120 kg ha^{-1}) and lowest in Limpopo (0.14 kg m^{-3}, fertilizer use < 30 kg ha^{-1}). Higher spatial variation in water productivity suggests greater chances to close the gap between the good and poor performers. Understanding the reasons for these differences at the regional or water-basin scale would both assess the potential for improvement and identify priority interventions in low-performing areas.

Causes of variation of water productivity

At the large scale of a country or river basin, besides the biophysical aspects, the level of socioeconomic development has a significant impact on agriculture. In most cases, the higher the contribution of agriculture to the gross domestic product, the higher the incidence of poverty (Hanjra and Gichuki, 2008). In turn, this limits farmers' capacity to increase inputs to agriculture, improve water productivity, and cope with droughts and floods. The African basins mostly rely on rain-fed agriculture with poor infrastructure, low inputs of fertilizers and irrigation, and consequently low crop yields and low crop water productivity. Water stress is a determining factor for all regions. Water for crop production is a concern in most areas including the extremely water-scarce basins. Water scarcity has worsened over the years and the trend will continue due to competitive demand from other sectors. Lack of appropriate diversion and storage structures exposes farmlands to droughts and sometimes even to floods.

Improved seed varieties, fertilizers, pesticides, and energy for tillage and other operations are critical inputs for large areas of low productivity. Land degradation is often another serious problem. Combined management of soil, water, plants and pests is required to overcome these constraints and secure improvements in yield (Bossio *et al.,* 2008) and water productivity. Additional threats are emerging in the form of environmental degradation and climate change. As agriculture intensifies it almost certainly has negative impacts on the environment (Bakkes *et al.*, 2009). In closed basins, where there is competitive demand for water, the need for environmental flows from the rivers is often ignored. The Yellow River ceased to reach the sea in the 1990s.The Indus is another closed basin where both surface water and groundwater are overexploited, causing significant declines in groundwater table, which threatens

sustainability of intensive agricultural systems (Sharma *et al.*, 2010). For the limited quantity of water left in rivers and aquifers, water quality often becomes a major concern. A survey in the Yellow River in 2007 found that about 34% of the river system registered a level lower than level V (Level Five) for water quality, which is considered unfit for any economic activity including agriculture. In the lower parts of the Ganges basin, arsenic contamination of groundwater is a threatening menace and is linked to overexploitation of groundwater (Chakraborty, 2004). Nonpoint source pollution from agriculture is a major threat to water quality in areas of intensive irrigation, where it is often accompanied by high fertilizer inputs (FAO, 1996). The severely degraded water quality threatens water supplies, and consequently, the water productivity. Similarly, climate-change-induced extreme climatic events, such as shorter and more intense rainy seasons and longer and more intense dry seasons will make agriculture, especially rain-fed agriculture, more vulnerable and thus lower the agricultural water productivity. However, further precise assessments of the impact of climate change on crop water productivity are especially needed.

Improving regional- or basin-level water productivity

Large gains in water productivity can be achieved by growing suitable crops in places where climate and management practices enable high water productivity and selling them to places with lower water productivity. Good analysis of basin-level water productivity maps helps compare the "bright spots" and "hot spots" to identify the visible yield gaps. Crop water productivity values with remote sensing at the pixel level provides explicit descriptions of both the magnitude and the variation (Figure 2) (Cai *et al.*, 2010, Zwart and Bastiaanssen, 2004). The next step is to make an assessment of the biophysical potential through local analysis based on solar radiation and soil of the region; to explore water-fertilizer applications in conjunction with crop-genetic innovations. This approach remains the major strategy to achieve the world's long-term goal of higher productivity and food security (Cai *et al.*, 2011). Improving WP through better water management is central to the solutions for improved productivity. Reliable, low-cost irrigation along with the critical inputs would enable poor farmers to improve their productivity.

Conclusions

During the last 50 years, the original concept of 'water-use efficiency' has been considerably enhanced to include 'crop productivity or value per drop of water'. In its broadest sense it relates to the net socio-economic and environmental benefits achieved through the use of water in agriculture. The more commonly used concept of 'water productivity' and its measurement at various scales is a robust measure of the ability of agricultural systems to convert water into food. Increasing water productivity is particularly important where water is scarce compared with other resources involved in production. While water productivity increases with increase in water supply up to

a certain point, water supply also improves fertilizer-use efficiency by increasing the availability of applied nutrients.

The complexities of measurements of physical or economic water productivity increase as the domain of interest moves from crop-plant to field, farm, system, basin, region and national level. An important fact to appreciate is that the water input to a field or an agricultural system is not the same as the water used or depleted for crop production as the water that is taken into the system, but not consumed, is available downstream and hence excluded from the estimation. Besides the conventional methods, the use of remote-sensing satellite data and crop modelling has helped comprehensively map the variations in basin- or regional-level water productivity and identify the potential areas for appropriate interventions.

Development of crop varieties with a higher harvest index during the Green Revolution era was the most successful strategy to improve land and water productivity, but further increases have slowed down. Additional increase in crop production is now achieved with near proportionate increase in water consumption leading to over-exploitation of water resources in the productive areas. Alternatively, dry-spell mitigation and soil-fertility management can potentially more than double the on-farm yields in the vast low-productivity rain-fed areas. Fertilizer-mediated better rooting increases the capacity of the plant to extract water by increasing the size of the water reservoir and extensive canopy with longer-duration increases in plant demand for water. Fertilizer rates (including secondary and micronutrients), over which farmers have better control, need to be adjusted properly in relation to available water supplies. Very low water productivity levels, even under water-scarcity conditions, might indicate that major stresses other than water are at work, such as poor nutrition and diseases. In large rain-fed areas of sub-Saharan Africa, often soil fertility is the limiting factor to increased yields. Achieving synchrony between nutrient supply and crop demand without excess or deficiency under various moisture regimes (including lowland paddy) is the key to optimizing trade-offs amongst yield, profit and environmental protection in both large-scale systems in developed countries and small-scale systems in the developing countries.

At large river-basin scales with diverse and interacting uses and users, the water productivity issues become increasingly complex. Options for improving water productivity include reallocation and co-management of the resources among the high-value uses while maintaining a healthy ecosystem. Appropriate water accounting procedures need to be put in place to identify the opportunities for water savings. Large gains in water productivity can be achieved by growing suitable crops in places where climate and management practices enable high water productivity and selling them to places with lower water productivity. Presently, there is great scope for increasing economic water productivity by increasing the value generated by water use and decreasing the associated costs. However, a number of key drivers including climate change, urbanization, changes in diets and populations, and change in prices of commodities (outputs) and inputs (seeds, fertilizers, energy, etc.) will require that systems need to rapidly respond to take advantage of potential gains in water productivity.

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Chapter 4

4R nutrient stewardship: A global framework for sustainable fertilizer management

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Harold F. Reetz, Jr.[1], Patrick Heffer[2] and Tom W. Bruulsema[3]

Abstract

Nutrient stewardship is the efficient and effective use of plant nutrients to achieve economic, social and environmental benefits with the engagement of farmers and other stakeholders. Nutrient stewardship aims at building capacity and assisting farmers and their advisers in continuously producing more food, feed, fiber and energy with less nutrient losses, thereby promoting sustainable agricultural intensification. Nutrient stewardship embraces concepts such as balanced fertilization and site-specific nutrient management, improved placement, timing of applications to coincide with plant nutrient needs, slow- and controlled-release and stabilized fertilizers, etc. Access to knowledge, all needed fertilizers and related services is an essential part of nutrient stewardship.

This chapter describes the concept, the scientific principles and implementation of 4R Nutrient Stewardship. Throughout the chapter, management of N on maize is used as the primary example, because maize is a widely grown crop throughout the world and N is often the nutrient of most concern for proper management in regard to agronomic, economic, social and environmental considerations. Variations of these discussions are applicable to other crops and other nutrients.

Introduction

Crop management systems and, especially, nutrient management systems, are developed from a collection of management practices selected by farmers and their advisers. Practices shown by research and experience to be more productive, more profitable, more environment-friendly, and more socially acceptable are designated as fertilizer (or nutrient) best management practices (BMPs).

[1] Reetz Agronomics, LLC, Monticello, IL, US, harold.reetz@reetzagronomics.com
[2] International Fertilizer Industry Association (IFA), Paris, France, pheffer@fertilizer.org
[3] International Plant Nutrition Institute (IPNI), Guelph, Ontario, Canada, tom.bruulsema@ipni.net

Through cooperative efforts of the International Plant Nutrition Institute (IPNI), The Fertilizer Institute (TFI), the Canadian Fertilizer Institute (CFI) and the International Fertilizer Industry Association (IFA), along with their members and other organizations, a global framework for sustainable fertilizer management was developed and is being adopted in many parts of the world. Described as "4R Nutrient Stewardship", it provides a framework for using the **right nutrient source**, applied at the **right rate**, at the **right time**, in the **right place**, to achieve improved sustainability. It presents a complete perspective of adaptive management of the life cycles of nutrients considering the economic, social and environmental performance of nutrient management practices. The 4R framework addresses the interests of all stakeholders: farmers; input suppliers; food, feed, fiber, and energy consumers; and those concerned about the environment and the related environmental services. It is being used to develop research and education programs, and management recommendations worldwide.

4R nutrient stewardship: The concept

4R Nutrient Stewardship is centered on four key areas of nutrient management:

- *Right Source* – Choose plant-available nutrient forms that provide a balanced supply of all essential nutrients with release matched to crop demand.
- *Right Rate* – Ensure an adequate amount of all limiting nutrients is applied to meet plant requirements in relation to yield and quality goals.
- *Right Time* – Time nutrient applications considering the interactions of crop uptake, soil supply, environmental risks, and field operation logistics.
- *Right Place* – Place nutrients to take advantage of the root-soil dynamics considering nutrient movement, spatial variability within the field, and potential to minimize nutrient losses from the field.

Furthermore, 4R Nutrient Stewardship considers the agronomic aspects of nutrient management relative to economic, environmental, and social goals for the specific site.

Box 1. Sustainability

The concept of sustainability provides the definition of "right" in the choice of source, rate, time and place of application. To be "right," the combination of these four management areas should enhance the sustainability of the cropping system, as reflected in the performance indicators, such as producer profitability (**economic**), food quality and nutritional value (**social**), and reduced nutrient loss to water bodies (**environmental**). The requirement for performance indicators relevant to the economic, social and environmental dimensions of sustainability is rooted in Brundtland's report "Our Common Future" (WCED, 1987).

4R Nutrient Stewardship requires the implementation of BMPs that optimize the efficiency and effectiveness of fertilizer use. The goal of fertilizer BMPs is to match nutrient supply with crop requirements to optimize yield while minimizing nutrient losses from fields. Selection of BMPs varies by location, and those that work best for a given farm will meet local soil and climatic conditions, crop type, management system, and other site-specific factors. 4R Nutrient Stewardship is a means by which the expectations of all stakeholders can be – and are – brought together for consideration.
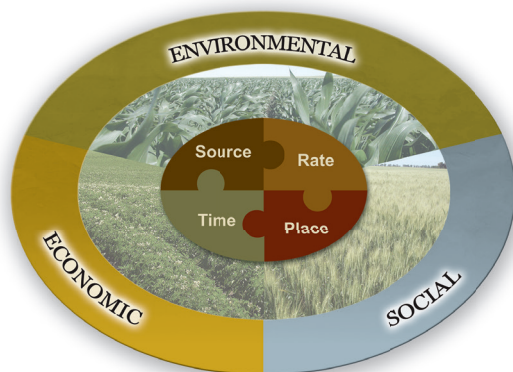
Figure 1. Diagram of the Global Framework for 4R Nutrient Stewardship. The concept is centered on the interlocking 4Rs, which influence the cropping system's contribution to the three dimensions of sustainability (IFA, 2009; IPNI, 2012).

Nutrient stewardship: Application of scientific principles

4R Nutrient Stewardship is based on a sound understanding of nutrient dynamics. Following are examples of how scientific principles of soil fertility and plant nutrition are involved in selecting source, rate, timing and placement combinations for nutrient applications.

Right source
The right source for a nutrient management system must ensure that a balanced supply of all essential nutrient elements is present in plant-available forms whenever required by the crop throughout the growing season. Selection of the right source must also consider susceptibility to nutrient loss, any nutrient interactions or compatibility issues, potential sensitivity of crops to the source, and risk from any non-nutrient elements included with the source material. The right source may vary with the crop, climate, soil properties of the field, available products, economic considerations and options for method of application.

Source options for nitrogen (N) include, among others, anhydrous ammonia, urea, urea ammonium nitrate (UAN) solution, calcium ammonium nitrate, and ammonium nitrate. For phosphorus (P), the most common sources are diammonium phosphate (DAP), monoammonium phosphate (MAP), triple superphosphate (TSP), and single superphosphate (SSP). A common fluid form is ammonium polyphosphate (APP). Potassium (K) is most commonly applied as potassium chloride (KCl); other sources include potassium sulfate and potassium nitrate. A diversity of sulfur, magnesium and calcium sources is available to farmers. A wide variety of trace elements is also marketed, including various sulfates, oxides, and chelates that range in solubility and plant availability.

In addition, several additives and treatments are commercialized to modify availability of the nutrients. These include products that break down gradually to release plant available nutrients (e.g. urea formaldehyde), that physically encapsulate fertilizer materials in a protective coating (e.g. sulfur- or polymer-coated fertilizers),or that chemically modify the rate of release of the nutrients from the fertilizer materials (e.g. fertilizers stabilized with urease or nitrification inhibitors) (Trenkel, 2010).

Several different options are available for slow- or controlled-release fertilizer materials. For example, the NPK granule in Figure 2 is coated with a polymer. This coating allows water to slowly enter the granule and dissolve the nutrients. Then the nutrients slowly move through the coating to the soil solution where they are available to the plant roots. The nature and thickness of the coating can be adjusted to regulate the rate of release of the nutrients as desired. While this formulation adds to the expense of the fertilizer, it also significantly improves the farmer's ability to manage the timing and rate of nutrient release. The controlled nutrient release allows better management of nutrient availability to the crop and also helps control losses to the environment.
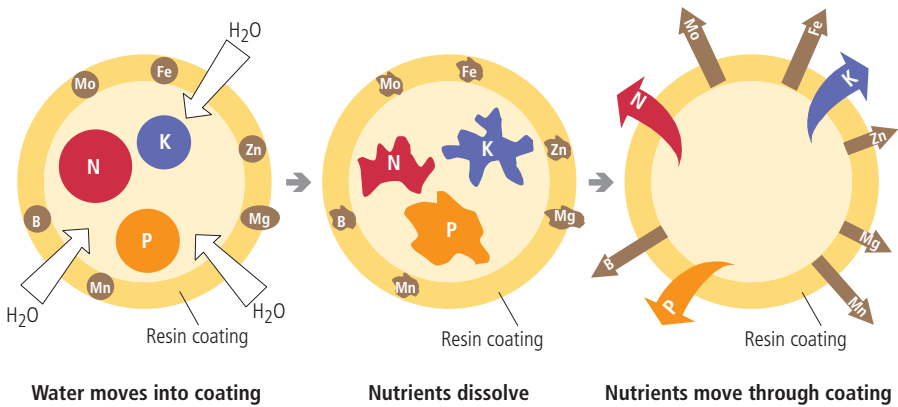

Water moves into coating **Nutrients dissolve** **Nutrients move through coating**

Figure 2. Mode of action of a coated/encapsulated controlled-release fertilizer (adapted from Trenkel, 2010).

In the past, such systems have been used primarily for high- value crops and turf but development of lower-cost materials in recent years has allowed new applications in commodity field crops. Controlled-release products continue to gain popularity because of their potential to substitute for split applications, thus addressing labor constraints while reducing losses to the environment and improving nutrient use efficiency.

Most controlled-release products are used for managing N release, but some are available for P. There are also a number of controlled-release micronutrient products where the coatings prevent leaching from the soil or help keep the nutrients in plant-available form by restricting reactions with soil minerals or organic matter.

Right rate

The right rate matches the plant-available supply of nutrients from all sources to the nutrient requirements of the plant. Understanding of the nutrient needs of the crop through the various growth stages is a first step to providing the right rate. Application rate should be selected to balance nutrient supply with crop demand throughout the growing season to avoid nutrient deficiency or excess. Crop yield and quality will be restricted if the rate is too low while excess application can lead to crop damage and negative environmental impacts. Both excess and insufficient nutrient application will decrease economic profitability.

In the 1970s, the common practice for commercial farmers in the United States was to apply enough N to ensure that it was not limiting. The price of N was low relative to the price of maize, and there was little concern about potential environmental consequences. Crop removal was only slightly higher than the current range of 11 to 13 kg of N per metric t of yield, but application rates were targeted at 21 to 27 kg N t^{-1} of expected yield. The cost of applying too much N was relatively low compared to the cost (in lost yield) of applying too little N. Prices have changed in recent years, making excess application uneconomic. In addition, improved management and better genetics have made crop nutrient use more efficient. Today, optimum N rates for maize are often lower than in the past, indicating increased N use efficiency. Current average application rates for maize in the United States range between 15 and 17 kg N t^{-1}, showing a sharp improvement in N use efficiency over the past decades.

The right rate for a crop can be determined with the help of a variety of tools. Rate studies from similar soil types and climate areas are a good place to start. On-farm rate tests are especially helpful because they match results with the farmer's own management. With modern rate controllers and yield monitors used in conjunction with soil tests, plant analysis, crop sensors, and field scouting, farmers and their advisers can design a rate program best suited to each field and management level, and implement it on a site-specific, variable-rate basis, matching the variability within each field. Such on-farm testing is important to help farmers make better-informed decisions on their fertilizer investment. Improved and site-specific N management can also be achieved with lower tech options, such as the leaf color chart for rice developed by the International Rice Research Institute (IRRI), and/or small test areas within a field. Measurement of crop yields in relation to the nutrients applied is the key element of the comparisons.
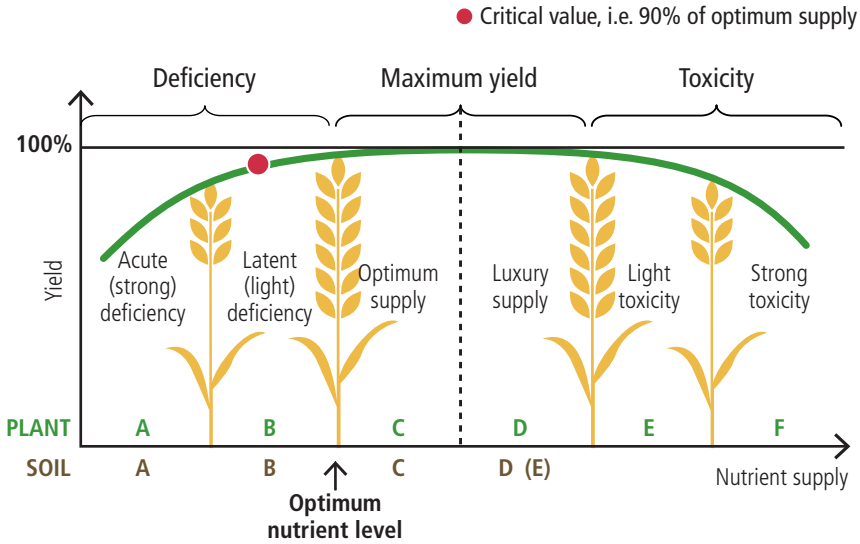
Figure 3. Effects of nutrient rate on wheat yield, showing potential deficiency and toxicity effects of not applying the right rate of nutrients (IFA World Fertilizer Use Manual, 1992).

Figure 3 illustrates the various sufficiency ranges for nutrients applied to a given crop. The optimum rate will supply nutrients slightly above the critical value, where further yield response to additional nutrient supply is not expected. The economic loss of supplying nutrients below that critical level is usually greater than the cost of supplying nutrients at a rate marginally above the critical level. Higher rates of some nutrients can lead to luxury consumption and, in extreme cases, to toxicity to the growing crop. Toxic application rates from fertilizers are not usually observed due to fertilizer cost. These higher levels should be avoided because they result in unnecessary fertilizer costs, potential loss of yield, and increased risk of nutrient losses to the environment.

The right rate should take into account all sources of nutrients, including soil supply (estimated using soil tests or omission plots[1]), manure and other organic sources, crop residues, biological N fixation, irrigation water and atmospheric deposition. There are important interactions to consider relative to rate. The right rate of N, for example, may be related to the amount of P, K or sulfur (S) available as optimum N response depends upon other nutrients being non-limiting. Rate comparison studies are an important part of determining the right rate. Rate studies are best done under the conditions for which the rate decision is being made, preferably on the farm, and considering other management factors, such as fertilizer placement, that may influence nutrient losses and hence rate of nutrient required.

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[1] Omission plots are a series of plots, preferably replicated, that omit one nutrient at a time, and are compared to plots with all nutrients to observe and/or measure the impact of that nutrient.

With precision-farming tools, spatial variation in nutrient needs within the field can be managed using variable-rate application of fertilizer. Variability in nutrient needs based upon soil tests and yield potential factors can be used to match variable-rate application to varying crop needs on a site-specific basis within the field.

Right time

Crop nutrient uptake rates change throughout the growing season as the crop moves from emergence to vegetative growth, through reproductive stages, and on to maturity. To attain optimum yield, sufficient plant-available nutrients must be present where the crop can access them to meet crop demand at all stages through the growing season. However, if the nutrient is present in the soil for an extended time prior to crop uptake, it may move out of the rooting zone or be converted to unavailable forms. The right timing of nutrient application will support crop yield and minimize nutrient losses.

A good example of timing for fertilizer applications based on stage of crop growth and nutrient needs is split-application of N for maize. An increasingly popular system for applying N to maize in the United States is to divide the application into two or three different times, often using different application methods and fertilizer sources. For example, a small amount of N may be surface applied as urea or UAN solution in the fall to stimulate soil microorganisms and help decomposition of previous crop residues, if those residues have high ratios of carbon to N. A second, pre-plant, application using banded anhydrous ammonia or UAN solution may then provide most of the N requirement, followed by a supplemental side-dress or top-dress application to fine-tune the total N program based on in-season monitoring, or predetermined total N rate plans. Reserving some N for a final application a few weeks after emergence (usually when the crop is 15 to 30 cm tall) allows for a more informed final decision on the total application rate based on a more accurate yield goal, reduces potential losses to the environment, and takes advantage of available precision technologies for varying the final application within fields. Some farmers may make a final top-dress N application of urea even later in the season, using high-clearance equipment, if additional N need is indicated. In West Europe, where the growing season is long and the potential for N loss is great, farmers usually split N applied to winter wheat into three or four applications to match the N supply to the dynamics of wheat N uptake.

Timing of application must also balance with weather conditions, other time-sensitive practices, the physical and logistical constraints of fertilizer application, and coordination with the height of the crop (for side-dress and top-dress applications).

The nutrient management plan should provide adequate amounts of available N in the soil to meet the crop's needs during its various growth stages. Figures 4a and 4b illustrate the growth stages of maize and the N requirements for different plant parts by the growing crop. Maize needs a small amount of N for early growth, large amounts in the middle of the season (when the stalk starts to elongate (about V8 growth stage), and lesser amounts during later grain fill. After pollination, as grain fill proceeds, the roots become energy-starved and less able to take up N, so it is important to have most of the total N requirement met and taken up into the maize plant by that time. Much of the N needed for the developing grain is provided by remobilizing N from lower leaves and
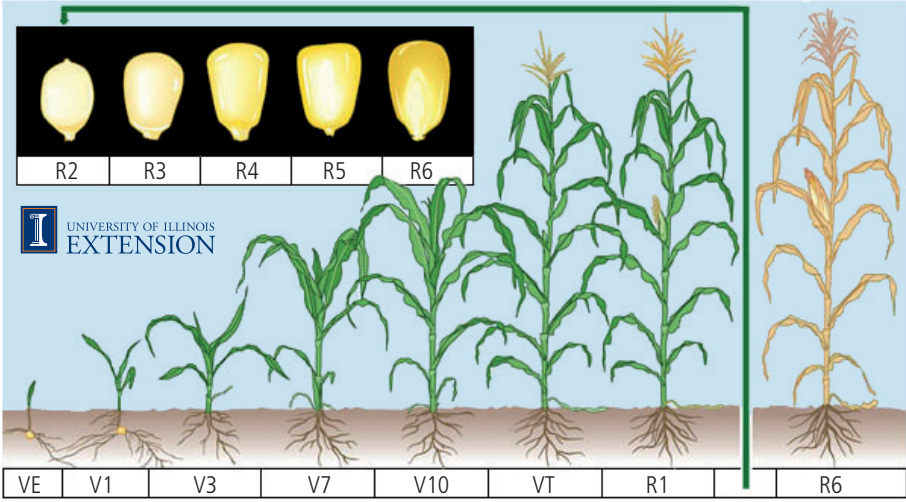
Figure 4a. Growth stages of maize (University of Illinois Extension, 2004).
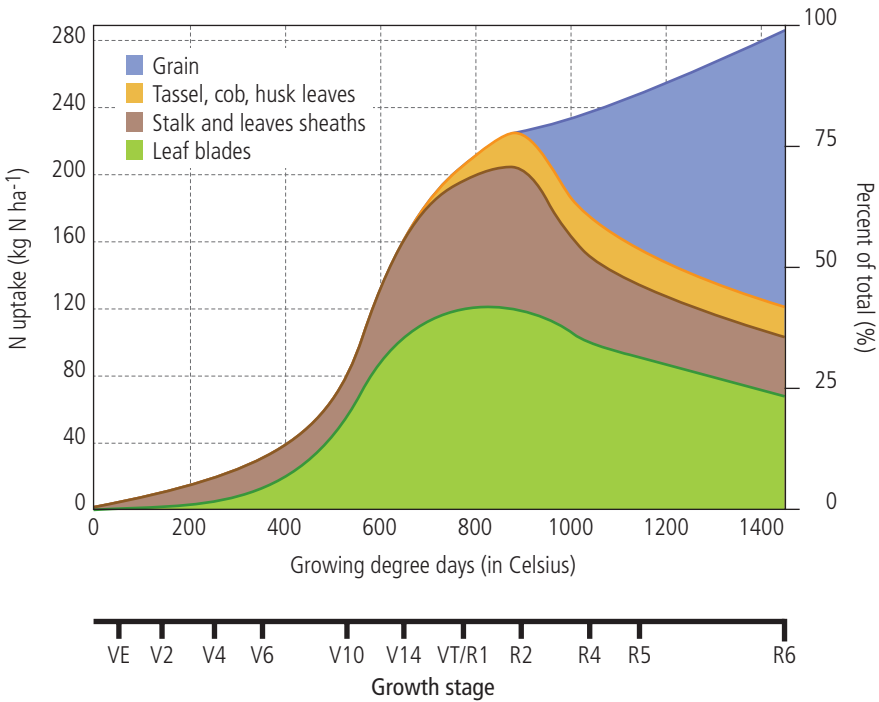
Figure 4b. Maize N uptake by growth stage: Timing of N uptake by maize and distribution of % total uptake within the plant (Bender *et al.*, 2013).

stalk. However, one of the ways to increase N uptake by the maize crop and improve N use efficiency is to maintain the health of the lower stalk and leaves to better supply carbohydrates to the roots.

Modern maize hybrids take up more N from the soil after pollination than older hybrids. Ensuring adequate N supplies in the later part of the growing season can be important for attainment of full yield potential. In some cases, a benefit to delayed application of N and use of nitrification inhibitor has been found to increase N uptake, yield and N use efficiency (Burzaco *et al.*, 2014).

In timing of nutrient application, the timing of processes influencing nutrient losses from the soil must also be considered. Timing is more important for nutrients that are mobile in the soil, like N, than for those that are retained by the soil, such as P and K. In the case of N, there are several processes of loss. Leaching and denitrification losses generally increase in wetter conditions. To minimize losses and improve N use efficiency, N application for any crop should be made as closely as possible before the time of rapid crop uptake, to ensure the crop growth needs are met, but potential N losses to the environment are minimized. In the case of P and K, most will be retained in the soil even when rainfall is intense enough to generate runoff, and timing of application has little impact on crop uptake. Surface applications of P, however, can dramatically affect water quality if they occur just a few days or weeks before a runoff event. To control impacts on the environment, timing of application of both N and P must be chosen with close attention to climatic conditions, soil type, and slope.

Another consideration for timing is crop sensitivity to specific nutrient deficiencies, often related to soil conditions. Transient trace element deficiencies may occur if soils are waterlogged, or if excess precipitation or irrigation promotes leaching of mobile nutrients below the rooting zone. For crops that are prone to certain micronutrient deficiencies, specific timing of nutrient application, or specific methods of application may be required to prevent or correct deficiencies. Plant analysis is often the best way to fine-tune micronutrient rates, because soil tests for micronutrients are often not reliable.

Right place

Having nutrients in the right place –vertically and horizontally– ensures that plant roots can absorb enough of each nutrient at all times during the growing season. Placement systems can be used to position fertilizer in relation to the growing roots. In recent years, availability of precision farming technology has made it also possible to fine-tune nutrient application, varying the rate of application within the field, to account for variability of soil test levels.

For placement with respect to the seed row and growing plant roots, there are several options:

- Surface broadcast and/or band application.
- Starter fertilizer application (traditionally 5 cm beside x 5 cm below the seed row for maize).
- Deeper banding (usually 10 to 15 cm below the surface), providing a concentrated nutrient source lower in the root zone.

- Strip-till systems, where a narrow strip (about 1/3 of the surface) is tilled and nutrients are concentrated in a band below the surface, maintaining a predominantly untilled surface residue environment to help reduce erosion and conserve soil moisture.

The right place also depends upon the characteristics of the fertilizer material being applied. Anhydrous ammonia, for example must be injected into the soil deep enough to seal the gas and prevent it from being lost to the atmosphere. Figure 5 illustrates the impact of placement of different fertilizer sources. Fertilizers applied to the soil surface are subject to potential losses in surface runoff. Other materials, such as urea or UAN solution, may be surface applied, but without incorporation into the soil, losses through volatilization can be substantial if sufficient rainfall or irrigation does not occur within a few days to move the fertilizer into the soil. Treatment of urea and UAN solutions with a urease inhibitor reduces volatilization losses and can enable successful use of surface applications in zero or reduced tillage systems. Slow- and controlled-release and stabilized fertilizer materials offer more placement options by protecting surface-applied nutrients from loss for a period of time ranging from a few days to a few months.
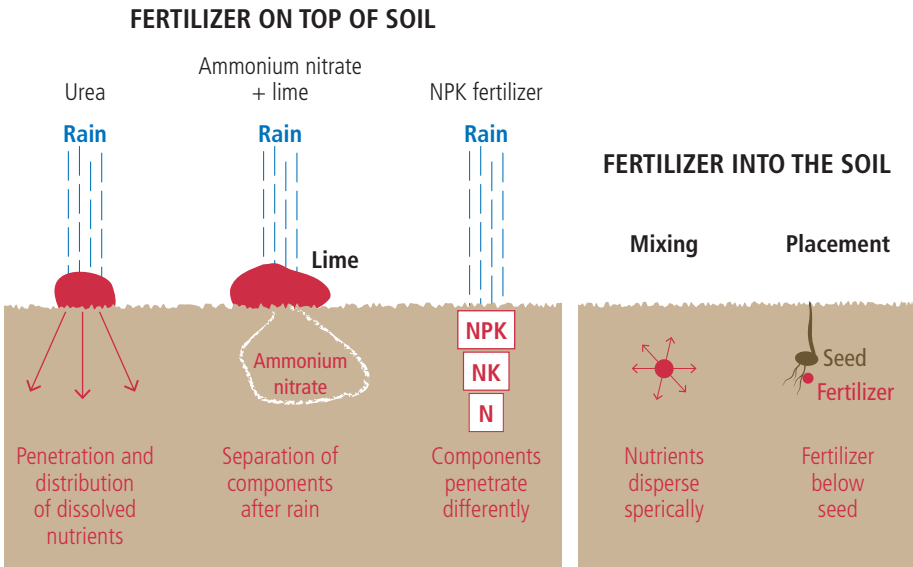
Figure 5. Impact of different fertilizer placement practices for movement of nutrients into the soil (adapted from IFA, 1992).

Mobile nutrients such as N or S can move in the soil water to reach the roots for uptake. In contrast, less mobile nutrients such as P and K will only move a small distance through most soil profiles. Therefore, for crops to access these nutrients, roots must contact the fertilizer reaction zone around the point of application. In particular,

placement in or near the seed-row may increase access of crops to the nutrient early in the growing season and provide a "starter" effect that improves early-season growth.

Placement can also be used to address spatial variation in nutrient needs within the field. With precision farming tools, fertilizers can be applied on a site-specific basis within the field, using variable rate application to match fertilizer applied to differing crop nutrient needs identified by soil tests, yield maps, and other methods of assessing variability in yield potential.

The placement of fertilizer affects both the current crop and subsequent crops. Figure 6 illustrates the effect of different fertilizer placement systems for non-mobile or slowly mobile nutrients, like P and K, over time. Repeated broadcast application results in a uniform horizontal distribution of nutrients concentrated near the soil surface, with the vertical distribution depending on the depth of incorporation. The nutrients gradually move down the soil profile deeper into the root zone. Band application using controlled guidance to place the band repeatedly in the same location results in a fixed band that tends to expand in size over time, but stays close to the same place, resulting in areas of high and low concentration. Band application, without controlled guidance, results in multiple randomly placed bands, and over time approximates the effect of broadcast application.

The uptake of fertilizer N early in the growing season can sometimes be enhanced by placing the N in a concentrated zone relative to the crop roots. But since N moves in soil solution and maize crop roots are well distributed, specific placement of N is probably not very important beyond the first few weeks of growth. For crops with a

Broadcasting nutrients over time (conservation tillage)

Banding nutrients in the same location over time

Banding nutrients in different locations over time

Increasing time
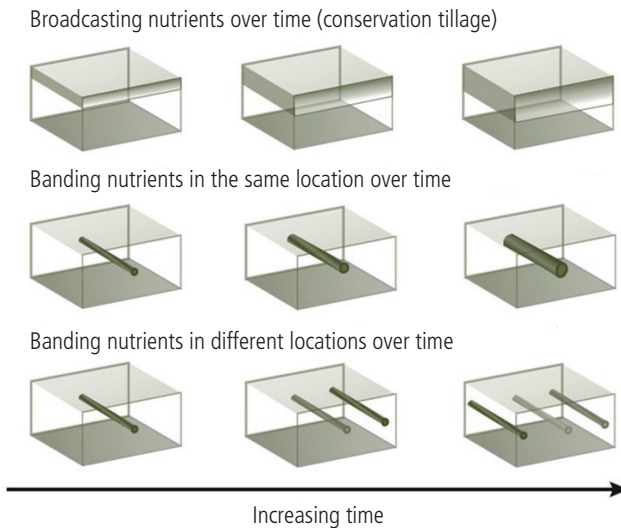
Figure 6. Effects over time of different types of fertilizer placement on fertilized soil volume (IPNI, 2012).

limited rooting system (e.g. lettuce), placement is more critical. Placement can affect susceptibility to N loss by runoff and volatilization. Simply incorporating the N into the soil with shallow injection or tillage can greatly reduce potential for these losses, and improve efficiency of utilization by the crop. Similarly, placement of an ammonia or ammonia-producing N source in a band may reduce risk of loss by denitrification or leaching by slowing the conversion of the ammonia to nitrate. Banding ammonium or ammonium-producing sources will be particularly important where the fertilizer will remain in the soil for a significant time prior to crop uptake, such as with fall application for a spring-seeded crop or with early spring application for a long-season crop.

Erosion losses are another aspect of economic and environmental concern. When soil erosion occurs, nutrients are moved along with soil particles and organic matter and thus become both an economic loss to the farmer and a potential environmental problem. Choices for 4R nutrient application need to be consistent with tillage and crop residue management practices for reducing erosion losses and keeping the nutrients in the field for the crops.

Nutrient stewardship: Implementation

Integrating sustainability goals and cropping system management objectives

Because nutrients are managed as one of several sets of inputs within cropping systems, sustainability goals must be translated into terms that are self-explanatory to cropping system managers. At the practical level, cropping systems are managed for multiple objectives. Fertilizer (or nutrient) BMPs should be selected in order to meet the agronomic and economic needs of farmers, but should also limit nutrient losses that impact the environment and ecological services the other stakeholders want to have protected. The appropriate BMPs are those that support multiple stakeholder objectives.

At the field level, it can be difficult to relate specific crop management practices directly to the economic, environmental and social pillars of sustainability. Therefore, it is useful to envision cropping system objectives as the vehicle for connecting practices to sustainability. System objectives vary with the region, sector and, often, over time, and they depend on the inputs of stakeholders as well, including those of farmers, consumers, rural residents, and other citizens. However, four common practical management objectives at the field or farm level are: productivity, profitability, durability of the cropping system, and environmental health.

These practices also affect the broader concept of soil health that relates to the long-term resilience and durability of the cropping system. The overall management system should contribute to the maintenance and improvement of soil health, and include nutrient availability, water-holding capacity, structure, biological activity and other measures.

Fertilizer BMPs are part of a larger, interlinked suite of nutrient, crop, soil, water and farm management practices. For a fertilizer management practice to be considered "best", it must harmonize with the other agronomic practices to address the full range of farm-level management objectives. The development, evaluation and refinement of fertilizer BMPs at the farm level must consider these multiple objectives, as must the selection of indicators reflecting their combined impact at different scales, from the field to the global level.

The set of cropping system management objectives at the field or farm level mentioned above can be defined and measured as follows:

- **Productivity.** For cropping systems, the primary measure of productivity is yield per unit area of cropland per unit of time and per unit of total inputs. The quality of the yield is part of the productivity measure. Both can influence profitability, through volume and value, respectively. Productivity should be considered in terms of all resources involved (e.g. land, water, energy, labor). Multiple efficiencies can and should be calculated to accurately evaluate productivity.

- **Profitability.** Profitability is determined by the difference between the value and the cost of production. Its primary measure is net profit per unit of cropland per unit of time. The profitability impact of a specific management practice is related to its economic efficiency, which is the increase in yield value compared to the cost of the practice.

- **Durability of the cropping system.** Durability refers to the ability of the cropping system to maintain resource quality over time. A durable production system is one where the quality and efficiency of the resources used do not diminish over time, so that for a cropping system outputs can be sustained or increased over time, without a need for increased inputs. With good management practices, system durability may increase, particularly on degraded soils, if increased crop productivity and photosynthesis lead to increased return of crop residues to the soil. Greater residue return can increase soil organic matter content, contributing to better soil health and improved productivity.

- **Environmental health.** Crop production systems have a wide range of effects on surrounding ecosystems through material losses to water and air. These impacts can be felt at local, national, continental or global levels. Specific effects can be limited or controlled by practices designed to optimize resource use efficiency. However, not all effects are controlled to the same level. Some environmentally important losses, such as those of P or nitrous oxide (N_2O), involve only a small fraction of the input applied. Others, such as ammonia (NH_3) volatilization or dinitrogen (N_2) emission from denitrification, may involve large losses, but are largely controlled by consideration of impacts on profitability.

Adaptive management

Nutrient management, and especially N management, is integrated with other crop management practices in developing a complete production system. To select fertilizer BMPs for a given field, it is important to use the best science available for optimizing the components of the system including their interactions.

Nutrient stewardship requires continuous adaptation to the evolving agricultural system in which it is implemented. An adaptive management process for development and adoption of fertilizer BMPs is required to respond to changing conditions in the production system (Figure 7). Adaptive management is a continuous loop that responds to the experience gained from implementing and evaluating practices. The farmer's experience, aided by research from universities and industry sources, guides the decision process. Site factors and stakeholder inputs supply additional information to be considered. The farmer ultimately makes the decisions on which practices and inputs are adopted or modified in the production system. He or she is also ultimately responsible for economic, environmental, and regulatory benefits and consequences. Analysis of the outcomes of these decisions provides feedback to adjust the management decisions for future action.

The nutrient source, rate, timing and placement decisions are interdependent, and the management objectives will vary according to local conditions, the farmer's objectives, and stakeholder input regarding the relative priority among system performance indicators. The relative importance of these objectives will significantly influence what is defined as "right" in terms of source, rate, timing, and placement. Sound science is essential to ensure that the practices chosen have the highest likelihood of attaining the management objectives.
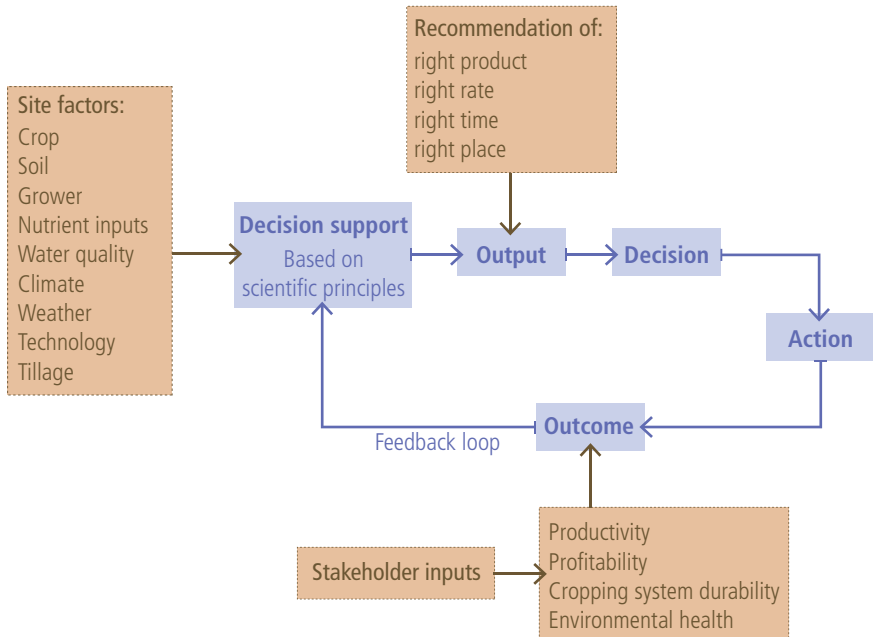
Figure 7. The role of adaptive management in practice refinement for 4R nutrient stewardship (adapted from IFA, 2009 and IPNI, 2012).

For each practice, it is important to consider the source, rate, timing and placement of nutrients. In most cases there are multiple options for each of the 4Rs in relation to each practice. As an example applicable to the maize-soybean rotation in the Lake Erie watershed in North America, Table 1 compares five different options for P application

Table 1. Advantages and limitations of selected P fertilizer application practices, combinations of source (S), rate (R), time (T) and place (P) for the maize (corn)-soybean rotation in the Lake Erie watershed in North America (Bruulsema *et al.*, 2012).

P application practice	Advantages	Limitations
OPTION 1		
S – MAP or DAP R – Removal rate for rotation T – Fall after soy before corn P – Broadcast	Minimal soil compaction Allows timely planting in spring Lowest-cost fertilizer form Low cost of application	Risk of elevated P in runoff in late fall and winter Low N use efficiency
OPTION 2		
S – MAP or DAP R – Removal rate for rotation T – Spring before corn P – Broadcast	Minimal soil compaction Better N use efficiency Low-cost fertilizer form Low cost of application	Risk of elevated P in spring runoff before incorporation Potential to late planting Retailer spring delivery capacity
OPTION 3		
S – MAP or fluid APP R – Removal rate for crop T – Spring P – Planter band	Best N efficiency Low risk of elevated P in runoff Less soil P stratification	Cost and practicality of planting equipment with fertilizer capacity Potential to delay planting Retailer delivery capacity Cost of fluid versus granular P
OPTION 4		
S – MAP or DAP R – Removal for crop or rotation T – Fall after soy before corn P – Zone placement in bands	Low risk of elevated P in runoff Better N and P efficiency Maintain some residue cover Allows timely planting in spring Less soil P stratification	Cost of RTK GPS guidance Cost of new equipment Requires more time than broadcast
OPTION 5		
S – Fluid APP R – Removal for crop or rotation T – Fall after soy before corn P – Point or spoke injection	Low risk of elevated P in runoff Better N and P efficiency Maintain good residue cover Allows timely planting in spring Less soil P stratification	Cost of RTK GPS guidance Cost of new equipment Cost of fluid versus granular P Requires more time than broadcast

MAP = Granular monoammonium phosphate.
DAP = Granular diammonium phosphate.
APP = Ammonium polyphosphate.
RTK GPS = Real-time kinematic global positioning system.

practices, showing the combinations of the 4Rs with the relative advantages and limitations for each combination. Such comparative evaluations provide the information needed to implement 4R Nutrient Stewardship.

Monitoring performance

The 4R framework relates to individual practices and their interactions for nutrient management in a cropping system. The impact of these practices on the economic, environmental and social effects of the cropping system is reflected by performance indicators that can be used to measure progress in sustainability improvement. Figure 8 depicts how some of the possible performance indicators relate to the economic, environmental and social dimensions of sustainable production.
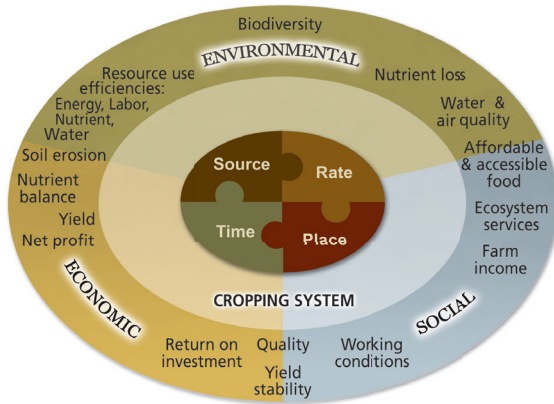
Figure 8. Performance indicators reflect the social, economic, and environmental aspects of the performance of the cropping system. Their selection and priority depends on stakeholder values. (IFA, 2009; IPNI, 2012).

The selected fertilizer BMPs are most effective when applied with other agronomic and conservation practices, as a part of a complete system of crop management. Poorly managed nutrient applications can decrease profitability and increase nutrient losses, potentially degrading water and air. Poor management of crop planting or tillage can cause the same effects. Due to multiple interactions of factors, it is essential that the entire system be considered when making management adjustments.

Table 2 lists some of the performance indicators associated with sustainable fertilizer BMPs, the kind of measurements used for those indicators, and the related sustainability goals associated with each indicator. It is important that various stakeholders' interests are considered in determining the relative order of importance among these and other indicators of sustainability. As stated earlier, the farmer makes the final decisions and accepts the consequences of the system he or she puts in place. Farmer interests and those

Table 2. Potential indicators for measuring sustainability of FBMPs (adapted from IFA, 2009).

Performance indicator (*)	Measurement	Comments	Related sustainability goals
Yield	Amount of crop harvested per unit of cropland per unit of time, and per unit of input.	High yields also reflect high net primary productivity, important for maintaining soil organic matter and soil quality.	Economic Social Environmental
Yield stability	Resilience of crop yields to variations in biotic and abiotic factors.	Reflects soil health.	Economic Social
Produce quality	Amount of crop constituents harvested (sugar, protein, minerals, etc.) or other attributes that add value to the harvested product.	Many mineral nutrients for plants are also important nutrients for people.	Economic Social
Soil productivity	Monitoring of soil organic matter and/or other soil quality indicators (to be determined) that reflect changes in soil productivity levels.	Contributes to clean water.	Economic Environmental
Nutrient balances	Budgeting of nutrient inputs and outputs, at the soil surface or farm gate.	Nutrient inputs match increasing removals associated with increasing yields.	Economic Environmental
Nutrient use efficiency	Yield or nutrient uptake per unit of nutrient applied.	Many expressions are available. Should be measured over multiple years.	Economic Environmental
Water use efficiency	Yield per unit of water applied or available.	Relevant to both irrigated and rain-fed production.	Economic Social Environmental
Energy use efficiency	Yield per unit of energy input.	Critically important for biofuel production.	Economic Social Environmental
Value/cost ratio of fertilization	Value of additional crop volumes and/or higher value of better- quality crop thanks to fertilization, relative to fertilization cost.	Reflects profitability of fertilizer use to the farmer.	Economic Social
Adoption	Proportion of producers using a particular BMP.	Depends on scientific linkage of the practice to its site-specific impacts.	Social Environmental

of other stakeholders may not be in agreement, and the interests of other stakeholders may be in conflict. So the farmer's final decisions must often be a compromise.

Highlights

- 4R Nutrient Stewardship aims to apply the right source of nutrients at the right rate, at the right time, and in the right place.
- "Right" is defined as the combination that improves overall sustainability of the cropping system considering economic, environmental and social perspectives.
- Scientific principles inform and guide the choice of right source, rate, time and place. Implementation is knowledge-intensive and site- and crop-specific.
- The 4Rs working in synchrony with other soil and crop management practices influence the performance of cropping systems. This performance includes the use efficiencies of nutrients, water, and all other factors of production.
- A cycle of adaptive management helps ensure that choices of management practices are effective in continuously improving the performance of the cropping system.
- Indicators that reflect the economic, social and environmental priorities of different stakeholders should be applied to demonstrate and communicate the outcomes in terms of improvement in the performance of the cropping system.

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Guiding scientific principles
(adapted from IFA, 2009)

All fertilizer BMPs

- **Be consistent with understood process mechanisms.**
  Take into account the related scientific disciplines, including soil fertility, plant nutrition, soil physics and chemistry, hydrology, and agro-meteorology.
- **Recognize interactions with other cropping system factors.**
  Examples include cultivar, planting date, plant density, crop rotation, etc.
- **Recognize interactions among nutrient source, rate, time and place.**
  For example, a controlled-release source does not need to be applied with the same timing as a water-soluble source.
- **Avoid detrimental effects on plant roots, leaves and seedlings.**
  For example, amounts banded near seedlings need to be kept within safe distances, recognizing ammonia, biuret, and overall salt index of the source.
- **Recognize effects on crop quality as well as yield.**
  For example, nitrogen influences both yield and the protein content. Protein is an important nutrient in animal and human nutrition, and it influences bread-making quality in wheat. Nitrogen rates above those needed for optimum yield may increase protein content, but over-application has a negative impact on plant health, crop yield and quality, and environmental sustainability.

Fertilizer source

- **Supply nutrients in plant-available forms.**
  The nutrient applied is plant-available, or is in a form that converts readily into a plant available form in the soil.
- **Suit soil physical and chemical properties.**
  Examples include avoiding nitrate application to flooded soils and use of surface applications of urea on high pH soils, etc.
- **Recognize interactions between nutrient elements and sources.**
  Examples include the phosphorus-zinc interaction, nitrogen increasing phosphorus availability, and fertilizer complementing manure.
- **Recognize blend compatibility.**
  Certain combinations of sources/products attract moisture when mixed, limiting uniformity of application of the blended material; granule size should be similar to avoid product segregation; fluid sources may "salt-out" at low temperatures or react with other components to form gels or precipitate.
- **Recognize crop sensitivities to associated elements.**
  Most nutrients have an accompanying ion that may be beneficial, neutral or detrimental to some crops. For example, the chloride accompanying potassium in muriate of potash is beneficial to maize but can be detrimental to the quality of some fruits and vegetables.

- **Control effects of non-nutritive elements.**
  For example, natural deposits of phosphate are enriched in several non-nutritive trace metals, including cadmium. The level of addition of these elements should be kept within acceptable limits.

Fertilizer rate

- **Assess soil nutrient supply.**
  Practices used may include soil and plant analysis, response experiments, or saturated reference strips.
- **Assess all available nutrient sources.**
  Includes quantity and plant availability of nutrients in crop residues, green manures, animal manure, composts, biosolids, irrigation water, atmospheric deposition and manufactured fertilizers.
- **Assess plant demand.**
  The quantity of nutrient taken up in one season depends on crop yield and nutrient content. Accurate assessment of attainable yield is important.
- **Predict fertilizer use efficiency.**
  Some loss is unavoidable, so to meet plant demand, the amount of loss must be considered.
- **Consider season-to-season variability in nutrient demand.**
  Yield potential and nutrient demand are affected by season-to-season variability in climate and other factors, including management, providing opportunities for real-time nutrient management with variable fertilizer rates (technologies include chlorophyll meter, leaf color chart, and other methods of in-crop nutrient assessment).
- **Consider nutrient budgets.**
  If the output of nutrients from a cropping system exceeds inputs, soil fertility declines in the long term. In the opposite situation, environmental quality and economic performance may be affected.
- **Consider rate-specific economics.**
  Taking into account spatial and temporal yield variability, for nutrients unlikely to be retained in the soil, the most economic rate of application is where the last unit of nutrient applied is equal in value to the increase in crop yield it is anticipated to generate (law of diminishing returns). Residual value of soil nutrients to future crops should be considered.

Fertilizer timing

- **Assess timing of crop uptake.**
  Depends on factors such as planting date, plant growth characteristics, sensitivity to deficiencies at particular growth stages. Nutrient supply must be synchronized with the crop's nutrient requirements, which usually follows an S-shaped curve.

- **Assess dynamics of soil nutrient supply.**
  Mineralization of soil organic matter supplies a large quantity of some nutrients, but if the crop's uptake need precedes the release through mineralization, deficiencies may limit productivity.
- **Assess nutrient release and availability from fertilizer products.**
  Release rate and availability of fertilizer nutrients are influenced by weather and soil moisture conditions at application, resulting in potential significant nutrient and yield losses if not synchronized with the crop's requirements.
- **Recognize timing of weather factors influencing nutrient loss.**
  Specific forms of a nutrient can perform better than others under certain climate conditions and in certain seasons. For example, in temperate regions, leaching losses tend to be more frequent in the spring and fall.
- **Evaluate logistics of field operations.**
  For example, multiple applications of nutrients may or may not combine with those of crop protection products. Nutrient applications should not delay time-sensitive operations such as planting.

Fertilizer placement

- **Recognize root-soil dynamics.**
  Roots of annual crops explore soil progressively over the season. Placement needs to ensure nutrients are intercepted as needed. An example is the band placement of phosphate fertilizer for maize, ensuring sufficient nutrition of the young seedling, increasing yields substantially even though amounts applied and taken up are small.
- **Manage spatial soil variability within fields and among farms.**
  Soils may affect crop yield potential and vary in nutrient supplying capacity or nutrient loss potential.
- **Fit needs of tillage system.**
  Recognize logistics of soil preparation. Ensure subsurface applications maintain soil coverage by crop residue and do not compromise seed-bed quality.
- **Limit potential off-field transport of nutrients.**
  Identify fields and field areas most prone to surface runoff, drainage discharge and gaseous losses. Keep nutrient losses through runoff, leaching, volatilization and denitrification within acceptable limits.
- **Reduce risk of nutrient toxicity on seedlings.**
  Avoid toxicity on seedlings from excess concentrations of nutrients in or near the seed-row.

The number of scientific principles applicable to a given practical situation is considerable. Narrowing down to a practical set of appropriate fertilizer or nutrient BMPs requires the involvement of individuals who are qualified to deal with these principles and knowledgeable in implementation. To varying degrees, producers and advisers need education on BMPs and their underlying scientific principles.

Chapter 5

Genetic improvement of water and nitrogen use to increase crop yields: A whole plant physiological perspective

Thomas R. Sinclair[1] and Thomas W. Rufty[2]

Abstract

Improvements in water and nitrogen (N) use "efficiencies" are often voiced as important targets for genetic modification in cropping systems. Although efficiency can be viewed in various ways, in modern agriculture the key relationship is the ratio of yield produced per unit of resource input. This review attempts to unravel the complex interacting factors that control the ratios and to identify possibilities for genetic improvement of crop plants to increase yields with limiting water or nitrogen input.

For the water use ratio, the inherent linkage between exchange of CO_2 and loss of water vapor through stomata makes it essentially impossible to decrease transpiration without penalizing photosynthesis and carbon inputs, and ultimately yield. However, genetic variation has been identified in stomata responses to high vapor-pressure deficits. Selection and refinement of this trait can lead to restricted transpiration rates at elevated vapor-pressure deficits that have minimal negative consequences for photosynthesis, and could lead to improved ratios of mass accumulation to plant water loss. A management-based approach to decreasing water loss is to use plants that can be sown at high densities and develop leaf canopies rapidly to shade the soil. These traits would directly minimize soil evaporation and, in cases with high off-season rainfall, allow plant development in periods with greater water availability.

Nitrogen acquisition by crop plants is closely aligned with meristematic activity and growth. A high degree of regulation at the biochemical level facilitates efficient N assimilation and conversions into protein and nucleic acids, but presents few opportunities for improvement. The critical trait for improving the N use ratio is to increase the proportion of applied N fertilizers taken up by the crop. The complexities of feedback systems controlling N transport in roots and integration of feedback loops with operations in the whole plant argue against successfully increasing nitrate uptake through genetic modification of individual genes. Modifications might be

[1] North Carolina State University, Raleigh, NC, US, trsincla@ncsu.edu
[2] North Carolina State University, Raleigh, NC, US, tom_rufty@ncsu.edu

possible if done at the process level through plant breeding that monitors whole plant performance. Increased N uptake may depend on parallel modifications increasing N storage capacities. Stored N must be in molecular forms that do not trigger feedback effects. Other options for increasing N uptake are to enhance early plant development to more closely align growth with fertilizer additions, increase root densities lower in the soil horizon, and sustain root growth and N uptake longer in the reproductive phase.

Introduction

The central goal of genetic improvement of crop plants is to increase yield. In the past, achievement of higher yields was often obtained by providing an abundance of resources to minimize limitations in reaching yield potential. Increasing economic and environmental costs, however, have imposed a need to optimize the application of input resources. Two of the main resources at issue are water and nitrogen fertilizer. A critical question facing all of agriculture is 'how can water and nitrogen use by crop plants be improved while still maximizing yield and economic return?' The objective of this chapter is to consider physiological alterations in crop plants that can maintain or increase crop yields in situations where inputs of water or nitrogen are limiting.

Although many different definitions have been used under the guise of 'water use efficiency' and 'nitrogen use efficiency', the legitimate goal must be to improve yield while minimizing water or nitrogen inputs. Such a 'resource use ratio' (yield/resource input) places preeminent importance on yield, the economic result ultimately required by farmers.

A critical challenge in the pursuit of genetic improvement of the water or nitrogen use ratio is that neither the numerator nor denominator is a simple genetic trait for either ratio. Regulation exists at the process level. With the involvement of a number of physiological mechanisms, it is unlikely that water and nitrogen use ratios can be improved by simple genetic alteration. Furthermore, because the controlling plant processes are strongly influenced by the environment, any genetic modification must be resilient across a range of environmental conditions.

The physiological processes controlling water and nitrogen use in higher plants are tightly integrated with whole plant functioning. Plants evolved for millions of years in environments often with limited availability of water and nitrogen. It should be no surprise that processes controlling acquisition of the two resources from the soil are well tuned to ensure competitiveness and survival. And, as a result of the natural selection, the controlling processes are part of complex systems of feedbacks and redundancies. It is, indeed, no small challenge to identify physiological failings in modern day germplasm that might be corrected to improve water and nitrogen use ratios.

In this chapter, we discuss regulation of water and nitrogen use ratios in crop plants, and attempt to identify strategies that can be exploited to increase whole plant growth and yield. The discussion reinforces arguments that controlling processes are too complex and too integrated into plant function to expect success using individual gene targeting and standard molecular manipulations. Within limits, some improvements of

the processes controlling water and nitrogen use are approachable using plant breeding and manipulations at the whole plant level.

Water use

Water is lost from leaves as a consequence of stomata opening to allow carbon dioxide to diffuse into leaves for photosynthesis (Figure 1). This is a physical process that occurs in higher plants, and there is no genetic solution to the obligate loss of water during the acquisition of carbon. The following development of equations help define the water use ratio at the leaf level.

$P_v{}^*$ water vapor pressure in the leaf

P_v vapor pressure of the surrounding atmosphere

Ci CO_2 to the interior of the leaf

Ca CO_2 from the atmosphere
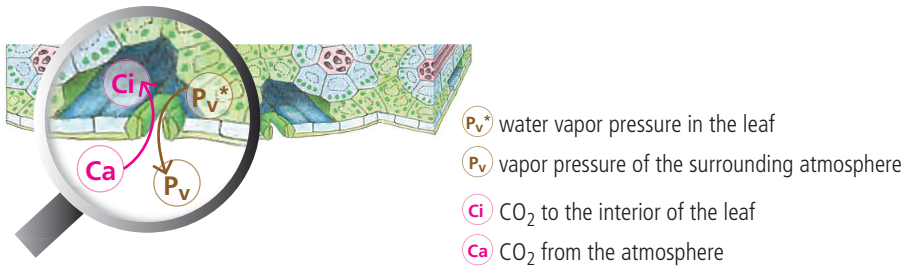
Figure 1. Cross-section of leaf illustrating the common diffusion pathway for CO_2 and H_2O.

Carbon acquisition (A) is defined by the gaseous conductance of CO_2 into leaves (h_c), and the gradient of CO_2 from the atmosphere (Ca) to the interior of the leaf (Ci). The value of Ca is essentially constant within a growing season, although it is clearly increasing with anthropogenic additions of CO_2 to the atmosphere.

$$A = h_c\,(Ca-Ci) = h_c\,Ca\left(1-\frac{Ci}{Ca}\right) \qquad [1]$$

The term (1–Ci/Ca) is a fairly stable ratio for each plant genotype. There is a tendency for stomata to respond to small changes in Ci so that the ratio Ci/Ca remains fairly constant. Among plants with high photosynthetic capacity, the C4 species have a minimum Ci/Ca of about 0.3 to 0.4 and C3 plants have a minimum Ci/Ca equal to about 0.65 to 0.7 (Tanner and Sinclair, 1983; Bunce, 2005). However, any genotype that is not operating at minimum Ci/Ca values clearly offers an opportunity to increase the ratio in water use. That is, those genotypes that are not operating at maximum capacity are potentially amiable to genetic alteration to decrease Ci, and increase (1–Ci/Ca).

Water vapor diffuses in the opposite direction of CO_2 (Figure 1), but is defined by a similar equation. Leaf transpiration (T_L) is defined by the gaseous conductance of water vapor (h_w), and the gradient of the water vapor pressure in the leaf ($p_v{}^*$) and the vapor pressure of the surrounding atmosphere (p_v). The value of $p_v{}^*$ is the saturation vapor pressure at the temperature of the leaf.

$$T_L = h_w \, (p_v{}^* - p_v) \qquad [2]$$

The water use ratio at the leaf level is obtained by dividing Eqn [1] by Eqn [2].

$$\frac{A}{T_L} = \frac{h_c}{h_w \, (p_v{}^* - p_v)} \; Ca \left(1 - \frac{Ci}{Ca}\right) \qquad [3]$$

The value of the ratio h_c/h_w is dependent on the transport properties of CO_2 and water vapor molecules in air. In the still air of the stomatal pore, which accounts for much of the physical limitation on gas conductance, the ratio h_c/h_w has a value of about 0.64 (Bierhuizen and Slayter, 1965).

An obvious approach to increase A/T_L for C3 species is to add the precursor phosphoenol pyruvate pathway to photosynthesis to achieve a low Ci. However, this approach has been shown to be a very difficult alteration in plants. Harold Brown and colleagues compared C3 and C4 activity in closely related *Panicum* species and interspecific hybrids between species. To achieve expression of C4 activity, it appeared necessary to have the full complement of C4 morphological and biochemical traits, which was not achieved in interspecific hybrids (Brown *et al.*, 1993; Brown and Bouton, 1993). Transgenic rice plants that produced manyfold higher levels of the key C4 enzyme phosphoenol pyruvate carboxylase in their leaves resulted in very modest increases in photosynthetic rates (Ku *et al.*, 1999).

Vapor pressure deficit $(p_v{}^* - p_v)$ is a physical term and seemingly not accessible for genetic alteration. However, recent studies indicate that a lower effective $(p_v{}^* - p_v)$ experienced by plants can be achieved by having limited transpiration rates under high $(p_v{}^* - p_v)$ conditions (Fletcher *et al.*, 2007; Gholipoor *et al.*, 2010; Devi *et al.*, 2010). Commonly, this trait is expressed as midday decreases in stomatal conductance, which limits the contribution of transpiration at this time to the total daily transpiration. As a result, the proportion of gas exchange occurring at times other than under high $(p_v{}^* - p_v)$ is increased, and daily gas exchange occurs at a lower effective $(p_v{}^* - p_v)$. Therefore, plant characteristics that enhance a midday decrease in stomatal closure would increase A/T_L. The problem, of course, is that midday decreases in stomatal conductance result in decreased A, and depending on the extent that it occurs, could ultimately decrease crop yield.

Canopy level

Tanner and Sinclair (1983) presented a derivation of the ratio between canopy growth (G) and canopy transpiration (T_C) starting with the leaf gas exchange equations (Eqns [1] and [2]). The result of their derivation of G/T_C for the canopy level had a form very similar to that of Eqn [3], although in detail it was much more complicated,

$$\frac{G}{T_c} = \frac{k}{(p_v{}^* - p_v)} \qquad [4]$$

The value of k was defined mechanistically based on the physics and physiology of gas exchange by the leaf canopy.

$$k = a\,b\,\frac{h_c}{h_w}\,Ca\left(1-\frac{Ci}{Ca}\right)\frac{L_D}{L_T}\frac{P}{\varepsilon\,\rho} \qquad [5]$$

where:

a = molecular weight ratio CH_2O to CO_2 (0.68)
b = conversion coefficient for hexose to plant mass
h_c/h_w = ~ 0.64
Ca = atmosphere CO_2 (400 µL L^{-1} = 0.73 g m^{-3})
Ci/Ca = ratio of leaf internal CO_2 concentration and atmosphere CO_2
L_D/L_T = ratio of leaf area in direct radiation (~1.4) to area of transpiring leaves (~2.2),
= ~ 0.64
P = atmospheric pressure (100,000 Pa)
ρ = air density (1,200 g m^{-3} @ STP)
ε = mole weight ratio of water vapor to air (0.64)

The value of b can vary a great deal among species based on the relative amounts of carbohydrate, protein and lipid synthesized by the plant. For example, the value of b for seed growth ranges among crop species from 0.42 for sesame seed to 0.75 for barley and rice (Sinclair and DeWit, 1975).

Due to variations among species in the value of b and (1–Ci/Ca), there are clear differences among species in the value of k. For a C4 species such as maize where (1–Ci/Ca) = 0.6 and b = 0.7,

$$k = \frac{0.68 * 0.7 * 0.64 * 0.73 * 0.6 * 0.64 * 10^5}{1{,}200 * 0.64} = 10.9\;Pa$$

For a C3 species such as wheat where (1–Ci/Ca) = 0.35 and b = 0.7,

$$k = 5.6\;Pa.$$

For a C3 species such as soybean where (1–Ci/Ca) = 0.35 and b = 0.50,

$$k = 4.6\;Pa.$$

In projecting possible increases in the intrinsic water use ratio by altering k, a critical question is the level of variability of k within a species. There are two components of k that could result in genotypic variability: (1–Ci/Ca) and the biochemical composition of the plant mass (b). As discussed previously, if any genotype has diminished photosynthetic capacity causing (1–Ci/Ca) to be low, then there is an opportunity to increase (1–Ci/Ca) and the value of k. However, cultivars that have already been selected for high yields under well-watered conditions are not likely to have low photosynthetic capacity.

The value of mass conversion coefficient "b" could be enhanced for a selected genotype within a species to increase the value of k by decreasing the fraction of lipid or protein synthesized, particularly in the seeds. The difficulty with this approach is that the economic value of a grain is defined to a large extent by the lipid and protein content of the seeds. The quality of wheat (*Triticum aestivum*) grain, for example, is determined to a large extent by its protein content. The value of soybean (*Glycine max*) seeds is dependent on both lipid and protein content. It is unlikely that the economic quality of the seeds can be sacrificed to alter the transpiration ratio.

The canopy transpiration use ratio as defined in Eqn [4] again highlights the role of $(p_v{}^*-p_v)$ in defining the transpiration ratio. As discussed previously, environments with low $(p_v{}^*-p_v)$ or plant traits that result in a low effective $(p_v{}^*-p_v)$ result in a high canopy transpiration use ratio. In the approach to limit transpiration at high $(p_v{}^*-p_v)$, decreased stomatal conductance and lowered CO_2 assimilation is likely the trade-off required to achieve a lower effective $(p_v{}^*-p_v)$.

Crop level

An evapotranspiration ratio for grain yield and total water loss can be described by two modifications of Eqn [4]. First, grain yield (Y) as a fraction of total plant growth (G) must be taken into account. This is accomplished by including the harvest index (Y = HI * G). Harvest index for modern crops is high approaching an apparent limit of 0.5 to 0.6. Further, HI has proven to be fairly stable for commercial cultivars over a fairly wide range of growth conditions, and commonly does not decrease unless substantial stresses are encountered (Spaeth *et al.*, 1984; Sinclair *et al.*, 1990). Second, evaporation of water from the soil surface (E) needs to be taken into account as a potential major contributor to total crop evapotranspiration (ET). By assuming that T_C and E are essentially independent of each other, ET can be expressed as following.

$$ET = T_C + E \qquad [6]$$

Rearrangement of Eqn [6] to define T_C and substitution in Eqn [4] results in,

$$ET - E = \frac{G\,(p_v{}^*-p_v)}{k} \qquad [7]$$

Since G = Y/HI, further rearrangement of Eqn [7] results in the following expression for the evapotranspiration ratio, Y/ET.

$$\frac{Y}{ET} = \frac{HI\left(1-\dfrac{E}{ET}\right)k}{(p_v{}^*-p_v)} \qquad [8]$$

In addition to the variables discussed previously as influencing transpiration ratio, Eqn [8] shows that the fraction of the total ET that is soil evaporation can have a large impact on Y/ET. Clearly a large value of E resulting in a large E/ET ratio will result in a decreased evapotranspiration ratio. Therefore, cropping practices resulting in lowered

E/ET so that an increased fraction of water is consumed as transpiration will improve Y/ET ratio. Narrow crop rows and low-tillage practices leaving crop residue on the soil surface will both help to decrease E/ET and increase this ratio.

Genetic improvement of transpiration water use ratio

The above analysis does not indicate any direct "attack point" for increasing the transpiration water use ratio. The critical variables of (1–Ci/Ca) and component plant products are not likely to be vulnerable to substantial change if selection pressure has already been applied in developing genotypes. Poor photosynthetic activity, i.e. low (1–Ci/Ca), and undesirable grain composition are likely to have been discarded for any species already subject to breeding pressure for economic yield.

One plant variable that might be improved is to decrease the ceiling $(p_v^*–p_v)$ under which crops allow gas exchange. Genotypes in several crop species have been identified that limit gas exchange under high $(p_v^*–p_v)$ conditions including soybean (Fletcher *et al.,* 2007), peanut (*Arachis hypogaea*, Devi *et al.,* 2010), and sorghum (*Sorghum bicolor*, Gholipoor *et al.,* 2010). The major benefit of this trait is water conservation. While limited gas exchange under high $(p_v^*–p_v)$ will result in decreased photosynthetic activity, the savings of water for use later in the season may commonly result in a yield increase, particularly if drought conditions occur. In simulation studies of this trait for sorghum in Australia, limiting transpiration rate to a maximum value under high $(p_v^*–p_v)$ resulted in a yield increase in about 75% of the growing seasons (Sinclair *et al.,* 2005). For soybean in the US, simulations indicated a yield increase in 80 to 85% of the growing seasons (Sinclair *et al.,* 2010).

Interestingly, an evapotranspiration water use ratio based on all available water to the crop (Eqn 8) indicates that decreasing the evaporation of water from the soil surface (E) may often be the most direct approach to increasing the ratio. That is, any method to decrease soil evaporation will increase the overall evapotranspiration water use ratio. Decreasing E can be aided by plant genetic alterations allowing early sowing under low $(p_v^*–p_v)$ and faster leaf canopy development to shade the soil surface. Also, plants that maintain high yield when grown in high plant densities or narrow rows will result in earlier shading of the soil surface and lower E.

Nitrogen use

Nitrogen is often the critical resource regulating plant growth rates and limiting crop yields. Plant modifications to improve plant growth per unit of N fertilizer being applied could help increase crop yields, and avoid the negative environmental consequences of N losses and contamination of groundwater. Much effort over the years has gone into identifying critical N components in cropping systems and attempting to modify them, and there have been some improvements through plant breeding (refer to Moll *et al.,* 1982, 1987; Sherrard *et al.,* 1984, 1986; Jackson *et al.,* 1986; Clark, 1990; Huggins and Pan, 2003). But improvements have not been large, so we can ask 'What further modifications can be made in plants to advance the nitrogen use ratio?'

The nitrogen uptake and assimilation pathway

The whole plant pathway for N assimilation involves a series of complex processes. In general terms, the sequence involves uptake by the root system, transport through the root symplasm to the xylem, long distance transport with the flow of water to mature leaves in the shoot, and assimilation into amino acids. The amino acids can be either incorporated into protein in the mature leaves or transported in the phloem to meristems where they are incorporated into proteins and nucleic acids, the fundamental components driving DNA replication and cell division. Cell division, i.e. meristematic activity is, of course, the primary event in the growth process.

Nitrogen acquisition from the soil is closely coupled with mass accumulation by plants, a relationship that has been demonstrated repeatedly over the years in models describing whole plant growth response (e.g. Thornley, 1976; Wann and Raper, 1979; Lemaire *et al.*, 2008). As pointed out by Clarkson (1986), N uptake is the 'pacemaker' of the growth process.

Successful strategies for improving the N use ratio in crop systems must include plant manipulations that increase N acquisition from the soil. Conceptually, improvements in inorganic N uptake could be achieved by increasing root development and the N absorption surface and by increasing uptake per unit of root. Both types of modifications are complex and must be considered with temporal and spatial factors in mind.

Fertilizer is applied to cropping systems prior to or in the early stages of plant development, and certainly in the early developmental stages of the root system. If significant rainfall occurs soon after sowing, large portions of the N can be leached from the soil profile, becoming unavailable to the plant and, subsequently, contaminating soil water supplies. Thus, advances in root competition for inorganic N will be dependent, at least in part, on modifications during the seedling and early vegetative growth phases. Clearly, the size of the root system is important, but so is the inherent activity of individual roots (Atkinson, 1990). Finer later roots, for example, very rapidly transport absorbed N to the shoot (Lazof *et al.,* 1992), providing the N supply that drives rapid growth of shoots.

After progressing into the vegetative growth phase, generally crop plants have a root density in the topsoil layers several fold greater than the 1.0 to 1.5 cm cm^{-3} required to access N in the soil solution. The requirement for a fairly low root length density threshold results from the high solubility of nitrate in the soil solution. Nitrate is the main inorganic N molecule in agronomic systems, and it moves readily to root surfaces by ion diffusion in the solution and by mass flow of the solution to the roots with the water being extracted from the soil. At greater depths in the soil horizon, root length densities can be often much less than the minimum threshold for N acquisition, even with the high solubility of nitrate. This is particularly true when downward root development is limited by a hard pan or by aluminum toxicity in acid soils.

Assuming that root morphological development positions absorbing surfaces in proximity to soil nitrate, it is not unreasonable to think that nitrate uptake might be improved by genetic modification of uptake processes. But, is there evidence that this approach can be successful?

Uptake of N from the soil solution occurs across the plasma membrane of root cells; probably epidermal or outer cortical cells at the root periphery (Kochian and Lucas, 1983; Clarkson, 1991). There are at least two pathways for nitrate uptake in the roots; a high-affinity pathway (generally K_m values < 20 µM) that saturate at external nitrate concentrations below 1,000 µM, and a low-affinity pathway where nitrate uptake increases linearly with increasing solution N concentrations (Glass, 2003). The pathways have a capacity for uptake that is generally well in excess of the amount of N actually taken up by roots *in situ*. Actual uptake rates are under tight plant regulation; both the high- and low-affinity pathways are subject to strict feedback control (Clarkson, 1986; Imsande and Touraine, 1994; Glass, 2003).

The feedback control mechanisms exist for nitrate and ammonium uptake (Glass, 2003). Evidence from a great many transport studies indicates that the feedback effects can emanate from signals associated with the ions themselves and from amino acid intermediates in the N assimilation pathway. Feedback regulation becomes engaged or released to varying degrees in response to internal or external factors that affect the growth process and 'demand' for N above- or below-ground. Shoot-based stimuli are able to engage feedback controls over N uptake by cycling amino acids downward to the root (Cooper and Clarkson, 1989).

Feedback control of inorganic N uptake into the root is influenced by a second transport step – N loading into the xylem. After absorption into cells at the root periphery, the majority of the nitrate moves inward across a series of cortical cells to the stele, where the ions cross another membrane and are loaded into mature xylem vessels. Many experiments, years ago, showed that regulation of xylem transport is separate from uptake into the root (Lauchli, 1976; Pitman, 1977; Touraine and Grignon, 1982; De Boer *et al.,* 1983).

In some situations, regulation of transport into the xylem may be responsible for decreases in uptake. A good example can be drawn from experiments with phosphorus and sulfur-stressed plants. In the very early stages of phosphorus and sulfur deficiencies, nitrate and amino acids begin accumulating in the root and, soon afterwards, nitrate uptake declines (Lee, 1982; Schjorring, 1986; Karmoker *et al.,* 1991; Rufty *et al.,* 1993). The response occurs prior to detectable changes in energy or growth in the root, and it implies that the ultra-sensitive xylem transport step is the trigger for engagement of feedback effects on uptake. This 'coordinated regulation' between the nutrient transport systems is a main factor in maintaining a stable nutritional composition in growing plants.

Additional evidence of the importance of xylem transport regulation lies in events occurring during the dark portion of the diurnal cycle. Nitrate uptake by the root proceeds during darkness, at a somewhat decreased rate, but a much larger proportion of absorbed nitrate is retained in the root (Rufty *et al.,* 1984). Retention in the root is regulated by inhibition of the xylem transport process, and the inhibition is independent of decreases in water flow (refer to arguments in Rufty, 1997). The xylem N transport regulation is sophisticated, being coordinated with stomatal opening and closure and the flow of water through the plant. Coordination is controlled by separate circadian rhythms that are kept in phase by the periodicity of light in the aerial environment

(Rufty *et al.,* 1989). The end result is that nitrate delivery to leaves is maximized in the light, when biochemical conditions are most favorable, energetically, for assimilation.

Biochemical manipulations of nitrate assimilations

Much research has investigated the physiology and biochemistry of N assimilation by higher plants. It has sometimes been assumed that a fundamental approach to increasing N use and plant growth exists at the biochemical level. But, it is highly questionable whether modifications of the N assimilation pathway would result in increased growth. An obvious problem, conceptually, is that enzymes that facilitate biochemical activity are reaction-specific, and millions of years of evolution have resulted in an assimilation system that typically avoids frivolous use of N.

When viewed within a biochemical framework, nitrate assimilation by crop plants exhibits characteristics of 'feed forward' and 'feedback' regulation. The feed-forward components begin with the inducible uptake systems operating at root cell membranes (Jackson *et al.,* 1973; Crawford, 1995; Daniel-Vedele *et al.,* 1998; Glass, 2003) and extend to part or full induction of several enzymes in the assimilation pathway (Campbell, 1996). As with uptake, feedback regulation exists for subsequent enzymatic components involved in assimilation.

Leaves are a primary site of nitrate reduction and further assimilation for the majority of crop plants. A close coupling between nitrate delivery to the shoot and leaf assimilation was demonstrated years ago (Shaner and Boyer, 1976). The key observation was that interruption of nitrate delivery led to a rapid decline in nitrate reductase activity (an inducible enzyme) even though leaf nitrate concentrations remained relatively stable. This implied rapid turnover of nitrate reductase, isolation of most of the nitrate found in leaf tissues, and the dependence of nitrate reductase induction on newly arriving nitrate from the xylem.

One of the deceptive aspects about nitrate assimilation in plants is the presence of unassimilated nitrate in plant tissues. If viewed strictly in a biochemical context, one might conclude that nitrate reductase limits nitrate assimilation. But, as implied by the Shaner and Boyer (1976) observations, nitrate is compartmentalized, presumably in vacuoles. Thus, accumulation of unassimilated nitrate likely results from competition between nitrate binding by the nitrate reductase enzyme and tonoplast transporters. Vacuolar nitrate can become available for reduction, but it is released only slowly. The release profile indicates stored nitrate serves as a reserve pool that can maintain or 'buffer' N-requiring plant processes through periods of low N availability (Rufty *et al.,* 1990; Chapin, 1991).

In the root system, there is also coupling between nitrate uptake into root cells and reduction, and as in leaves, a portion of the entering nitrate enters storage pools (MacKown *et al.,* 1983; Rufty *et al.,* 1984; Jackson *et al.,* 1986). In this case, at least in maize (*Zea mays*), nitrate compartmentation is associated with localization of nitrate reductase in outer, peripheral cells of the root and nitrate accumulation in cortical cells closer to the root interior (Rufty *et al.,* 1986). After uptake into cells at the root periphery, a portion of the entering nitrate is reduced, but most of the nitrate transits through the root cortex and stele to the xylem. The symplastic pathway evidently isolates nitrate

from the bulk cytosols, preventing induction of nitrate reductase and reduction along the way. While assimilation and compartmentation of nitrate both occur, the majority of the nitrate taken up by roots in most species is transported to the shoot.

Viewing whole plant nitrate assimilation events on daily time scales, it is apparent that N assimilation is a very efficient, high through-put process. Biochemical components are finely-tuned, limiting accumulation of intermediates and facilitating the reactions that feed into protein and DNA synthesis. Even with the translocation delay that occurs with nitrate retention in the root in darkness, the majority of nitrate is translocated, assimilated and incorporated into macromolecule end-products in leaves within hours of absorption. Indeed, ^{15}N experiments indicate that 80-85% of the N taken by plants is assimilated into protein within 12-24 hours (Rufty *et al.,* 1984).

One should not be confused by the excess accumulations of particular amino acids that occur under conditions of stress. Under water stress, for example, proline can sometimes accumulate in leaf tissues (Bloom *et al.,* 1985; Munns, 2002). And during phosphorus stress, arginine can accumulate (Rabe and Lovett, 1986; Rufty *et al.,* 1993). In both cases, however, accumulations are quantitatively small when expressed as a percentage of the N absorbed and thus do not represent major diversions from the N flow to meristems. When water and phosphorus stresses occur, as with the many other stresses that interfere with plant growth, the main plant response is to slow N uptake.

Almost uniformly, enhanced expression of specific enzymes in the N synthesis pathways have failed to influence overall plant performance. Many examples can be used to demonstrate this point. One of the most compelling examples comes from overexpression of nitrate reductase using molecular genetic manipulation (Vincentz and Caboche, 1991; Campbell, 1996, 2002; Curtis *et al.,* 1999). Although increased nitrate reductase expression decreased nitrate concentrations in tissues, growth was not increased. These efforts followed years of work to increase nitrate reductase activities using plant breeding (Sherrard *et al.,* 1984, 1986), which found the same result. Higher nitrate reductase activities were not associated with increased growth and yield. Some hopeful signs came from overexpression of asparagine synthetase genes, but growth benefits were present only under low solution N concentrations (Good *et al.,* 2004). This result is not relevant to cropping situations where large amounts of N must be taken up by crops to drive rapid growth and meet the needs of the harvestable plant material. Similarly, transgenic canola (*Brassica napus*) with overexpression of alanine aminotransferase and enhanced accumulation of alanine in roots (Good *et al.,* 2007) produced greater plant mass than wild-type plants under low fertility. Under more relevant conditions of high N supply, there were no differences in plant mass or seed yield. And a last example comes from studies with transgenic wheat where increased cytosolic glutamine synthetase during leaf senescence appeared to increase grain yield of individual plants in the greenhouse (Habash *et al.,* 2001). But, there has been no confirmation that the effect occurred in the field or that the hypothesized mechanism of enhanced mobilization of N from senescing leaves of the transgenic plant was correct.

Carbon assimilation and storage modifications

Another option for increasing the N use ratio might be to increase photosynthesis and the total amount of C in the plant. The N use ratio at the plant level has often been defined, historically, as plant growth (G) divided by the total amount of N accumulated by the plant (N_{accum}) (Moll *et al.*, 1982). Therefore, the ratio G/N_{accum} is seemingly positively correlated with G, or with the leaf level CO_2 assimilation rate.

At any point during plant development, much of the N in leaves is in the photosynthetic enzyme ribulose 1,5-bisphosphate carboxylase/oxygenase (RuBisco). In wheat and rice, for example, the fraction of total leaf N in RuBisco is about 25% (Makino, 2011) while in soybean it is about 50% (Wittenbach *et al.*, 1980). One consequence of the high amounts of N in the photosynthetic apparatus is a nonlinear correlation between leaf N and leaf photosynthesis rate that seems to be well defined for each crop species (Figure 2a). There is a diminishing return in increased A as leaf N increases, ultimately approaching a maximum rate of A.

The explanation of the maximum A is that photosynthesis is limited by the availability of CO_2 in the vicinity of Rubisco. Physical constraints on CO_2 diffusion into and within leaves ultimately control the rate of carbon assimilation in leaves. This is the basis for predictions that increases in the atmospheric CO_2 concentration will lead to C_3 plant species having somewhat increased A and increased ratio A/N.

Field measurements indicate that a nearly unique A relationships exists for each crop species across various leaf N levels (Figure 2a). These relationships can be used to calculate A/N as a function of leaf N (Figure 2b). Maximum A/N occurs at very low N for maize and rice of 0.6 and 1.3 g N m^{-2}, respectively. Due to the high N of soybean leaves, the maximum A/N occurs at 2.5 g N m^{-2}. The leaf photosynthesis rate at maximum A/N occurs at about only two-thirds maximum A in all species.
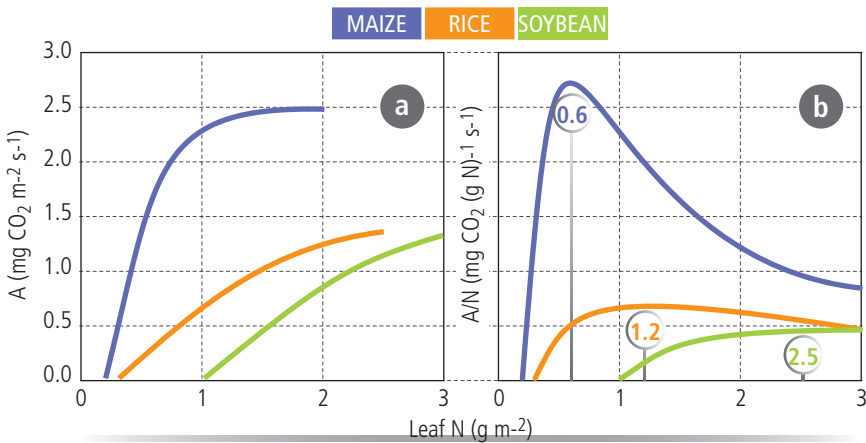
Figure 2. (a) Leaf photosynthesis rates as a function of leaf nitrogen content per unit area of three crop species. (b) Ratio of photosynthetic rate (A) divided by leaf N content as a function of leaf nitrogen content for each crop species.

If unique relationships between A and N illustrated in Figure 2a can be altered for a particular species, then there would be the potential to increase the N use ratio. It has been proposed that the performance of RuBisco might be enhanced so that lower amounts of the enzyme, and lower amounts of N, are needed to sustain high rates of photosynthesis (Whitney *et al.,* 2011). However, transformations that altered fractions of leaf N as Rubisco did not alter the photosynthetic rate of rice (*Oryza sativa*) leaves (Suzuki *et al.,* 2007). Another approach was to transform rice to undertake C4 photosynthesis, which would increase A/N, but increasing the amount of phosphoenolplyruvate carboxylase did not result in the desired large increase in A (Ku *et al.,* 1999).

With any attempt to modify the relationship between N assimilation and photosynthesis, it is necessary to be continually aware of the complexities involved. Carbon and N assimilation systems are the two major synthesis pathways in plants, and the two systems are interdependent throughout a plant's life cycle (Thornley, 1976; Wann and Raper, 1979; Rufty, 1997). The interdependency between carbon and nitrogen assimilation systems extends well beyond biochemical controls and into whole plant processes like carbon partitioning (Rufty *et al.,* 1988) and shoot-to-root growth ratios (Ingestad and Lund, 1979; Chapin, 1991; Rufty, 1997). Any plant modifications that alter photosynthesis or carbon assimilation could have a series of unintended consequences that are negative factors for increasing the N use ratio.

On the other hand, the most advantageous approach for increasing carbon inputs may be to increase rates of leaf area expansion, and thus total crop photosynthetic capacity. The highest rates of plant growth appear to reflect an optimized leaf canopy N concentration that establishes the best balance between A and leaf area (Sinclair and Horie, 1989). When modifying leaf area, it must be assumed that plants would continue to optimize the distribution of N among leaves at different canopy positions. Top leaves generally have the highest N concentrations and the highest photosynthetic activity
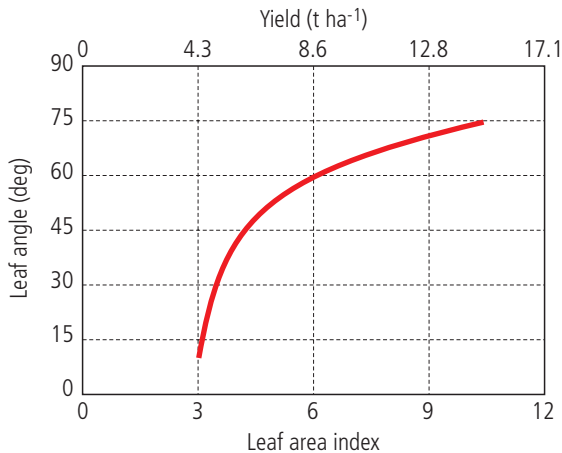
Figure 3. The relationship of leaf angle on increasing leaf area index and increasing grain yield (Sinclair and Sheehy, 1999).

(Shiraiwa and Sinclair, 1993; Sadras *et al.,* 1993; Wang *et al.*, 2005). And benefits from increased canopy leaf area may also depend on adjustments in leaf canopy architecture. Erect leaves allow light penetration deeper into the canopy to minimize early senescence of leaves and, potentially, sustained photosynthetic activity during seed growth (Sinclair and Sheehy, 1999). The relationships between increasing leaf angle and the potential for greater yield are demonstrated in Figure 3. Although experimental evidence is still somewhat limited, one should also be aware that increased leaf angle may not always offer advantages for increased productivity at high plant densities (Hammer *et al.,* 2009).

Increased leaf area not only enhances the opportunity for greater capacity of crop photosynthesis, but increases storage of N during vegetative growth when the majority of the N is being acquired from the soil. Even if N storage in leaves is increased beyond that required for maximum A/N, more N is available for transport to the seeds during reproductive development. Nitrogen can be stored in Rubisco, which is a comparatively stable protein. Its degradation is highly controlled by proteases, and amino acid degradation products are readily translocated to the developing grain (Feller *et al.,* 2008).
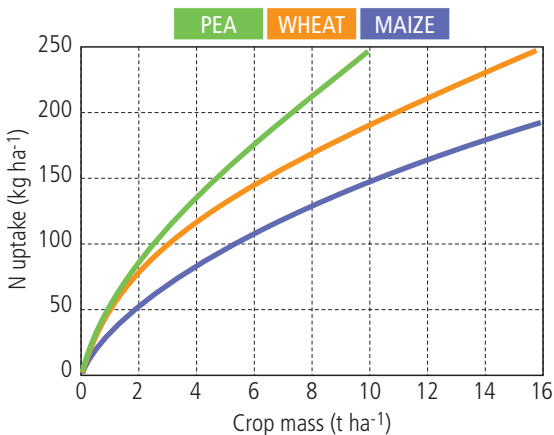
Figure 4. Nitrogen storage capacity in three crop species plotted as a function of the crop mass at the end of vegetative growth. The calculation of nitrogen storage was based on the relationships estimate of crop nitrogen concentration as a function of crop mass (Lemaire *et al.*, 2008).

Variation of species exists in the amounts of N storage in leaf tissues. In its simplest form, increases in total N storage during vegetative growth will be related to increases in leaf mass, and thus total crop mass. The positive correlation between N concentration and crop mass allows calculation of N storage potential of crop species (Figure 4). Maize has the least storage capacity due to a low N content of leaves, which is associated with the C4 assimilation pathway. Wheat, with large amounts of RuBisco to support C3 photosynthesis, has a larger storage capacity. Pea had the greatest storage capacity, likely associated with the leaf paraveinal cells (Lansing and Franceschi, 2000).

Crop level modeling of the N use ratio

Separate from considerations of N physiology and biochemistry, possibilities for increasing the N use ratio can be evaluated from field observations. Yield (Y) can be expressed as a simple function of N_{accum}, i.e. modifying the N use ratio to grain yield (Y) divided by N_{accum}. Since harvested seeds include a large fraction of the N in the plant, Y is by definition equal to the amount of N supplied to seeds divided by the N concentration of the seeds ($N_{seedconc}$). The nitrogen supplied to the seeds can be expressed as the total N_{accum} accumulated by the crop multiplied by the fraction of the plant N that is in the seeds at maturity (that is, nitrogen harvest index, NHI). This relationship is expressed in the following equation.

$$Y = \frac{N_{accum}\ NHI}{N_{seed\ conc}} \qquad [9]$$

Rearranging

$$\frac{Y}{N_{accum}} = \frac{NHI}{N_{seed\ conc}} \qquad [10]$$

Equation [9] indicates that crop yield and N_{accum} are closely related to each other. The implication is that it is very difficult to increase yield without similar increases in N. Historically, a close coupling between the two factors has been maintained (Sinclair and Sinclair, 2010).

To what extent could Y/N_{accum} be altered to increase the N use ratio? One approach, as illustrated in Eqn [10], is allowing $N_{seed\ conc}$ to decline. With some crop species, the market place imposes major constraints that preclude decreases in $N_{seed\ conc}$. The economic value of wheat and soybean, for example, are both determined to a large extent by their seed protein concentration, and there are major monetary penalties if the concentrations are lowered. But market constraints have not been prohibitive for change in maize. The seed protein concentration decreased 0.03% year^{-1} as yields in the US increased between 1960 and 1991 (Duvick, 1997).

Does an increase in NHI offer an approach to increase Y/N_{accum}? In most modern crops, the value of NHI has been increased to about 80% of the total N in the plant, reflecting improvements in mobilization of materials from vegetative tissues to the seeds during reproductive growth. The 20% of N_{accum} remaining in senesced leaves and stems is committed to structural components, which are necessary for maintaining the integrity of the plant and not available for transfer to the seed. It is difficult to envision decreasing the fractions of N in the structural components much further. Therefore, little or no future opportunity exists to further increase NHI.

Given the constraints on A, and on NHI and $N_{seed\ conc}$, Eqn [10] shows there are limited options for increasing Y/N_{accum}. Of course, an important extension of this ratio is Y divided by the amount of N fertilizer applied to the soil (N_{appl}). The ratio of Y/N_{appl} can be evaluated by recognizing that soil applied nitrogen is either accumulated by the

crop (N_{accum}) or becomes unavailable in the soil for use by the crop ($N_{unavail}$) as a result of several processes.

$$N_{appl} = N_{accum} + N_{unavail} \qquad [11]$$

The amount of N fertilizer in the soil that is eventually unavailable to the crop results from microbial growth, denitrification in anaerobic sites in the soil and from leaching in the soil below the rooting zone. Under good conditions, N_{accum} is commonly less than 0.6 of N_{appl} (e.g. Alvarez *et al.,* 2008; Giacomini *et al.,* 2010), and in many cropping

$$\frac{Y}{N_{appl}} = \frac{N_{accum} \, NHI}{N_{seed \, conc} + (N_{accum} + N_{unavail})} \qquad [12]$$

Rearranging Eqn (12), the following expression results.

$$\frac{Y}{N_{appl}} = \frac{NHI}{N_{seed \, conc} + (1 + \frac{N_{unavail}}{N_{accum}})} \qquad [13]$$

situations, the ratio of N_{accum}/N_{appl} is 0.4 or less. Clearly, increasing N fertilizer recovery can have a large impact on the N use ratio of crops, defined as Y/N_{appl}.

The Y/N_{appl} can be expressed mathematically by dividing both sides of Eqn [9] by N_{appl}. Substituting the definition of N_{appl} given in Eqn [11] to the right-hand side of the equation results in the following relationship.

Eqn [13] illustrates that the critical term explaining much of the variation of Y/N_{appl} is the ratio $N_{unavail}/N_{accum}$. As the amount of $N_{unavail}$ in the soil increases relative to N_{accum}, the denominator in Eqn (13) increases, resulting in decreased Y/N_{appl}. This analysis shows that to increase Y/N_{appl}, it is necessary to shift more of $N_{unavail}$ to N_{accum}.

Genetic improvement of nitrogen use ratio

From the previous discussion, we cannot point to a gene or even a group of genes that are potential targets for genetic manipulation to improve growth or yield under field conditions. This puts us at odds, in general, with the push to improve N use using molecular biology approaches (refer to Hirel *et al.,* 2007). All indications are that increased acquisition of N is essential for increasing the N use ratio, but molecular studies to identify and overexpress nitrate transporters in roots is not likely to be productive (refer to Miller *et al.* 2007; Glass, 2009; Kant and Rothstein, 2011). In our view, the complexities of the feedback system in roots and its integration with operations in the whole plant argue against successfully increasing nitrate uptake through genetic modification of individual genes. There are simply too many points of integration with whole plant regulatory functions, and downstream effects could nullify seemingly positive modifications and have negative consequences for plant performance.

Genetic modification strategies

We do feel that some genetic improvements are accessible through plant breeding. The advantage is selection of traits that are imbedded within whole-plant responses. Moving modifications to the process level, along with continual evaluation of impacts on plant performance, raises the possibility of successful manipulation. Indeed, any advances in crop growth and yield in the field environment, including those under less than favorable conditions like drought, would likely be accompanied by increased uptake of applied fertilizer N because of the linkage between growth and its nitrogen driver.

- One particularly attractive target is increasing germination and seedling vigor and growth in the early vegetative phase. This will synchronize root development and plant N demand with the time of N fertilizer application. Improved early growth potential, along with management adjustments to position fertilizer appropriately, will maximize uptake of applied N fertilizer and decrease losses to the environment.

- Enhanced recovery of nitrate moving deeper into the soil horizon would be possible with genetic modifications that adjust root architecture to increase growth deeper into the soil. Deeper root growth, in turn, may depend on genetic modifications to overcome physical (e.g. plow pans) or chemical (e.g. aluminum toxicity) obstructions in the soil horizon.

- Increases in N acquisition beyond those associated with growth can occur only with greater N storage that does not engage feedback effects. This requires increases in N containing macromolecules like Rubisco. Or, it could involve establishing or increasing amounts of glycoproteins like those in the leaf paraveinal cells of some legumes (Klauer *et al.,* 1996; Lansing and Franceschi, 2000). Attempts to increase storage are unlikely to be successful if they depend on large accumulations of nitrate or amino acids. Vacuolar storage capacity is limited and the probability exists for feedback inhibition of transport processes.

- Increases in NHI might be successful if Rubisco stability and/or N storage are increased. More functional N in leaves counterbalances the senescence causing events of protein degradation and transfer of N to grain, and extends photosynthetic activity. Stabilization of N proteins and N containing macromolecules, analogous to the 'stay green' property (Borrell *et al.,* 2001), would benefit from more erect leaves and increased penetration of light into ever more dense leaf canopies. Extension of photosynthesis longer into grain filling would also be accompanied by enhanced carbohydrate transport to the root system and extending the period of active root growth and function. This, in turn, could increase acquisition of nitrate present in the soil late in the crop growing season. Higher amounts of N assimilated during grain fill would further counterbalance degradation losses in leaves and, perhaps, allow NHI to increase in parallel to NHI.

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Chapter 6

Crop productivity and water and nutrient use efficiency in humid and subhumid areas

Wade E. Thomason[1], Abdoulaye Mando[2], André Bationo[3], Maria Balota[4] and William Payne[5]

Abstract

There is a strong need to improve the efficiency of water and fertilizer use by agriculture in humid and subhumid areas as highlighted in this chapter. Recent reports conclude that 75% of agricultural water use is attributable to rain-fed production systems, which are the most common production schemes in humid and subhumid zones. It is useful to think of maximizing the efficiency of water inputs, either natural or irrigation, in order to achieve the most efficient overall cropping system. However, in the humid and subhumid areas of the world, the most efficient cropping system is often one that optimizes crop production per unit of land, and not necessarily per unit of water. Optimizing production requires the efficient and strategic use of fertilizers to achieve high yields. Strategies that sacrifice yield in favor of avoiding total loss to drought are generally not favored in these environments because the extent and duration of moisture stress are unknown; nor is the occurrence of drought highly predictable. There is significant opportunity to improve water use in rain-fed systems as compared to irrigated production; and fertilizer input to increase crop yield is one of the most important factors to achieving better water use efficiency for many crops in humid and subhumid zones. We suggest that opportunities exist in many cropping systems worldwide to better manage fertilizers and thus water utilization through: 1) better synchrony between crop demand and fertilizer supply, 2) increased use of banding nutrients to increase availability via positioning, 3) addressing spatial and temporal variability in nutrient needs, 4) more efficient capture and use of rainfall, and 5) supplemental irrigation.

[1] Virginia Tech, Blacksburg, VA, US, wthomason@vt.edu
[2] GRAD Consulting Group, Ouagadougou, Burkina Faso, amando@gradcg.com.
[3] Action for Integrated Rural Development (AIRD), Accra, Ghana, abationo@outlook.com
[4] Virginia Tech, Suffolk, VA, U.S., mbalota@vt.edu
[5] University of Nevada, Reno, NV, U.S., bpayne@cabnr.unr.edu

Climate classification, plant growth and water use

With today's large climate databases and increasingly powerful geographical information system (GIS) software, there are many ways to classify climate at increasingly fine scales. But the most widely used system remains that of Köppen (1884) or modified versions thereof (Ritter, 2006). By 1875, the idea that climates might be classified according to the type of vegetation or physiological response they produced was well established (Thornthwaite and Hare, 1955). Köppen's (1884) earliest classification was based only on temperature and the period during which temperature was above a certain threshold value. His system recognized that vegetation in the temperate hot summer climate and subtropical belts suffered regularly from drought. High temperature in these belts, he states, only indirectly affected vegetation by increasing evaporation, but for the most part high temperatures mainly occurred in the summer with little cloudiness and rainfall. Therefore, heat and water shortage were closely related and formed a clear-cut line between the northern forest region and the deserts or steppes in continental areas. However, there were other parts of the subtropical and hot summer climate belts where heat and high humidity occurred simultaneously, such as the monsoonal areas of South and East Asia, and the south-eastern edge of North America and Brazil. This combination of heat and high humidity also characterized the tropical belt for a major part of the year. His subsequent world map (Figure 1) included precipitation as well as temperature, both of which are climate characteristics that are easy to measure, and for which there are long historical records. Köppen (1918) defined the main climatic zones as: (A) tropical rain climate, (B) dry climate, (C) warm temperate climate, (D) sub-arctic climate, and (E) snow climate.

So we have known that crop growth has something to do with temperature, water, rainfall and humidity for some time. Subsequent empirical climate classification systems have been based on an aridity index, such as those of Thornthwaite (1948).

Humid and subhumid zones typically have adequate precipitation to support crop growth during the greater part of the year, so non-irrigated agriculture has traditionally been the norm. Such zones can be delineated to a first approximation from a simple but useful system proposed by the United Nations Conference on Desertification (UNESCO, 1977) that is based on annual precipitation (Pr) and potential evapotranspiration (PET). In this approach, delineation occurs by dividing the annual precipitation (Pr) by the annual PET. Subhumid, moist subhumid and humid zones are thus defined as having $0.50 \leq PrPET^{-1} < 0.65$, $0.65 \leq PrPET^{-1} < 1.0$, and $PrPET^{-1} \geq 1.0$, respectively. These ratios have served as a general guide for classifying different regions, but one must bear in mind that Pr, soil water storage patterns, and length of growing season vary widely among sites falling into the same $PrPET^{-1}$ classification. Cropping systems have been developed that fit seasonal patterns of rainfall and avoid anticipated periods of prolonged drought.

In drier climatic zones, precipitation tends to be low and erratic, and other environmental stresses, such as high temperature, are common. These climates are also characterized by high radiation levels throughout the growing season. In such zones, yield (Y) is almost always a function of crop transpiration (T), and free water
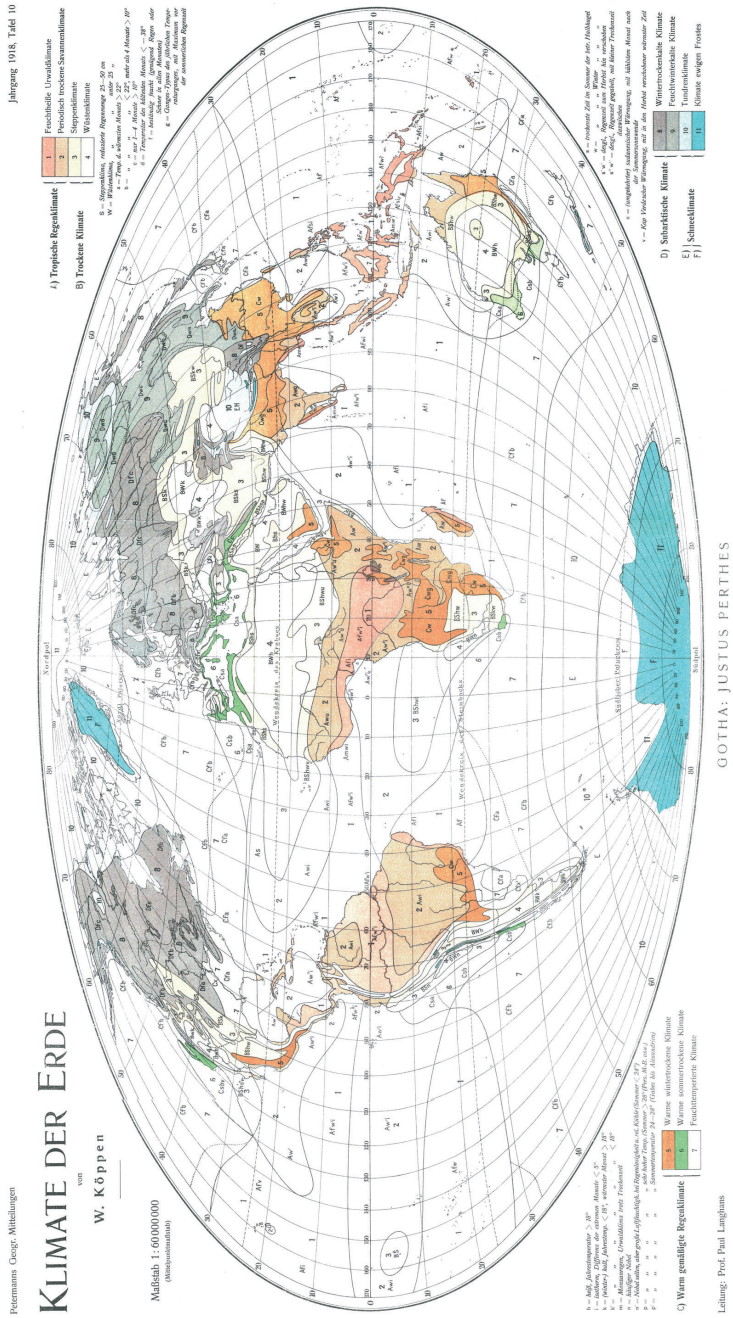
Figure 1. Köppen climate classification scheme dividing climates into five main groups.

evaporation (E_0) when there is adequate water for growth, as shown by de Wit (1958) in his classic paper:

$$Y = mTE_0^{-1} \qquad \text{[Eq. 1]}$$

where,

Y = crop aboveground dry matter or marketable yield (g),

T = total transpiration for growth (kg),

E_0 = evaporation from a free water surface (mm day^{-1})

m = the crop factor (often kg ha^{-1} day^{-1})

In humid and wet subhumid areas where free water evaporation rates are generally lower, the relationship of yield per unit of water transpired is not directly related to E_0 but rather to intercepted radiation. For these climates, de Wit proposed that E_0 can be neglected giving:

$$Y = nT \qquad \text{[Eq. 2]}$$

where,

n = the crop factor (often in kg ha^{-1} mm^{-1})

In 1958, de Wit thoroughly analyzed and interpreted the relation of transpiration and production of single leaves (net assimilation), single plants grown in containers, and field crops. He was the first to realize the importance of potential evapotranspiration (water evaporated per unit time from an extensive 'free water surface') in explaining yield and transpiration relations in dry zones, and radiation in humid zones, as shown by Eqns. 1 and 2. These observations suggest that, depending on the climate, strategies of increasing crop production could be different. In dry climates, production is not limited by net assimilation rate (A), but rather by T, as in this climate Pr is usually low. Irrigation would seem to increase T and therefore biomass production, but WUE decreases because evaporation (E) increases too, in particular under low fertility or any other condition in which canopy is not fully closed and direct soil evaporation prevails. In humid and subhumid climates, production is limited by A, but T can easily reach a maximum since Pr is usually higher or equal to PET. As A cannot be substantially increased by modification of plant chemistry for either C_3 or C_4 photosynthetic pathways, increasing light harvesting would seem more reasonable to consider in this environment. This may include increasing leaf area index (LAI), leaf area duration, leaf erectness, and canopy closure.

Several other models were developed to explain the relation of net photosynthesis and transpiration, and T efficiency in the mid- to late 1900s, including the Bierhuizen and Slatyer (1965) model. These authors expressed net photosynthesis per leaf area as a function of CO_2 concentration in the air, the CO_2 compensation point, and the boundary and stomatal resistances to CO_2 diffusion. Transpiration was related to vapor pressure deficit, and boundary and stomatal resistances to water vapor was corrected by air density and atmospheric pressure. Then, they assumed that the relation of net photosynthesis and transpiration was proportional to Y and T on a field basis and assumed that:

$$Y = k\,T(e_s - e_a)^{-1} \qquad \text{[Eq. 3]}$$

where,

e_s = saturation vapor pressure (mbar),

e_a = actual vapor pressure (mbar),

k = the crop coefficient (mbar^{-1})

To better explain the variability of k among species and depict "some insight into the causes of minor variations of k within a species" Tanner and Sinclair (1983) further built upon Bierhuisen and Slatyer's model to include new arguments such as leaf area index (LAI) and shading of the leaves within a canopy. The authors further compared estimated k values with observed k values obtained from experiments in dry and humid climates. Observed and calculated k values were consistent for drier climates, but not for the single humid-zone experiment (Netherlands). By way of explanation, the authors suggest that this divergence was at least partly due to the much smaller vapor pressure deficit (VPD) in the humid compared to drier environments. Interestingly, when replacing T by evapotranspiration (ET) to evaluate ET rather than T efficiency, Tanner and Sinclair realized that E can be approximated empirically as the intercept on the ET axis only when plotting cumulative Y *vs*. cumulative ET for a season. But "this does not apply to a graph of seasonal Y *vs*. seasonal ET using different field plots that have been differently irrigated". In this latter case, E will differ between treatments and similarly ET and VPD will differ. These observations are in agreement with de Wit's (1958) analysis clearly showing that the relationship between Y and T cannot be explained in humid environments by using ET and VPD. Optimizing productivity in humid and subhumid climates could then be achieved by optimizing energy capture and utilization rather than optimizing output per unit of water. Nonetheless, improved water use efficiency appears to be easier to achieve and economically more advantageous in humid areas with low VPD than in arid environments, based on the historical data.

Current status of fertilizer and water use efficiency in humid and subhumid zones

There is an urgent need to develop sound technologies for resource management that maximize the efficient use of water and nutrients to achieve sustainable agricultural production (Zougmoré, *et al*., 2004). In many countries, limited water is a major impediment to effective crop nutrient uptake and use efficiency, while nutrients are often the most limiting factor to water productivity in humid zones (Hatfield *et al*., 2001). Data from Zimbabwe from 1979 to 1997 show a similar relationship between country gross domestic product (GDP) and rainfall variability (Figure 2) indicating great dependence of the two factors and highlighting the threat from global climate variation.

Indeed the strong interaction between water and crop nutrient availability arises from the various effects of water on (1) the conversion of nutrients from unavailable to available forms; (2) the transport of nutrients to the plant roots; and (3) nutrient loss processes through erosion and leaching with drainage.
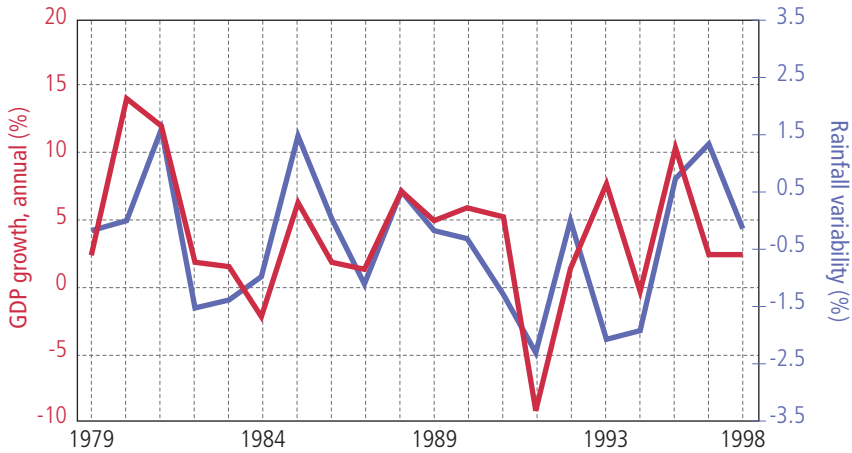
Figure 2. Relationship of rainfall variability (deviation from the long-term mean) and GDP growth in Zimbabwe, 1979-1997 (Richardson, 2007).

Fertilizer use efficiency by plants in subhumid regions is largely dependent on the amounts of rainfall, and fertilizer, especially, nitrogen response under agricultural dry periods is very limited (Greenland, 1985). Therefore in subhumid zones, it is essential that water constraints be addressed in combination with soil nutrient constraints. This is important because investments in water management alone may not generate the payback required to make the effort worthwhile. In a recent study, Zougmore *et al.* (2005) showed that investment in water management requires a simultaneous investment in soil fertility management in order to generate the economic benefits needed to make efforts in water harvesting worthwhile.

In humid zones, water use efficiency is frequently limited by nutrient availability (Viets, 1962). In these areas, influencing water losses through management of drainage and runoff can help limit nutrient losses through leaching and erosion, thus increasing productivity per unit of fertilizer input (Basso and Ritchie, 2012).

Brouder and Volenec (2008) state that the predicted effects of climate change on nutrient and water use efficiency will be plant- and site-specific and that both management and crop improvement will be needed to mitigate potential negative effects. They suggest that in areas and for crops where nutrient and water use efficiency are already well managed, this trend will continue. In areas or systems with poor or less than optimum use of water and nutrients, climate change will exacerbate existing problems.

There is significant opportunity to improve water use in rain-fed systems through best management practices of fertilizer that increase crop yield. We suggest that opportunities exist in many cropping systems to increase fertilizer and water utilization through site-specific nutrient management, implementation of best management

practices of fertilizer, and increased use of banding nutrients to increase availability via positioning and addressing spatial and temporal variability in nutrient needs.

Why focus on humid and subhumid areas?

In many instances, managing crops to maximize the efficiency of water input, either natural or irrigation, achieves the most efficient overall cropping system (Sinclair *et al.*, 1984). However, in humid and subhumid climatic zones, the most efficient cropping system is often one that optimizes crop production per unit of land, and not necessarily per unit of water (Viets, 1962). In these areas, water stress is typically infrequent in fall-seeded crops since ET is below P for most of the growing season. Water stress in spring- and summer-planted crops is often intermittent in time course and duration, meaning that stress can occur at any time from emergence to maturity, with varying intensity (Green *et al.*, 2000). Strategies that sacrifice yield in favor of avoiding total loss to drought are generally not favored in these environments because predictability of the extent and duration of moisture stress is poor.

There is a strong need to improve the efficiency of water use by agriculture in the humid and subhumid areas highlighted in this chapter. Recent reports conclude that 75% of the approximately 7,100 km^3 year^{-1} of water used by agriculture is attributable to rain-fed production systems, which are the most common production scheme in humid and subhumid zones (de Fraturier *et al.*, 2007). Water use in rain-fed systems is generally less efficient compared to full irrigation programs, mainly due to the lack of correspondence in time between crop water demand and water supply (Rockström *et al.*, 2010). However, the ability to expand or even maintain full irrigation capacity is unlikely to improve due to competition with human populations over freshwater resources, contamination of freshwater, and dwindling supplies of groundwater in some regions. The predicted effects of climate change (IPCC, 2007), such as rainfall declines in many areas with marginal yields under rain-fed conditions and of more extreme and variable climate events worldwide, also dictate that we pay more attention to agricultural water use in humid areas. So there is a need for not only greater efficiency of water and plant nutrient use but also systems and techniques that increase the resiliency and sustainability of food production in rainfall-based agriculture (IPCC, 2007).

Subhumid zones and cropping systems

Subhumid zones exhibit native vegetation that ranges from grasslands and bushes to woodlands depending on moisture and soil resources (Hess and McKnight, 2011). Soils are generally inceptisols, mollisols, and alfisols (Awiti *et al.*, 2007). In subhumid and moist subhumid zones, annual mean rainfall is generally adequate for seasonal annual crop production. However, due to variation in the time and volume of precipitation, water deficit can and does occur (Figure 3). High-level agricultural production in these areas generally benefits from deficit or limited irrigation timed to supply supplemental moisture at times of greatest crop demand. Season-wise, this can occur during the dry season or when evapotranspiration is greatest. During the rainy season, precipitation
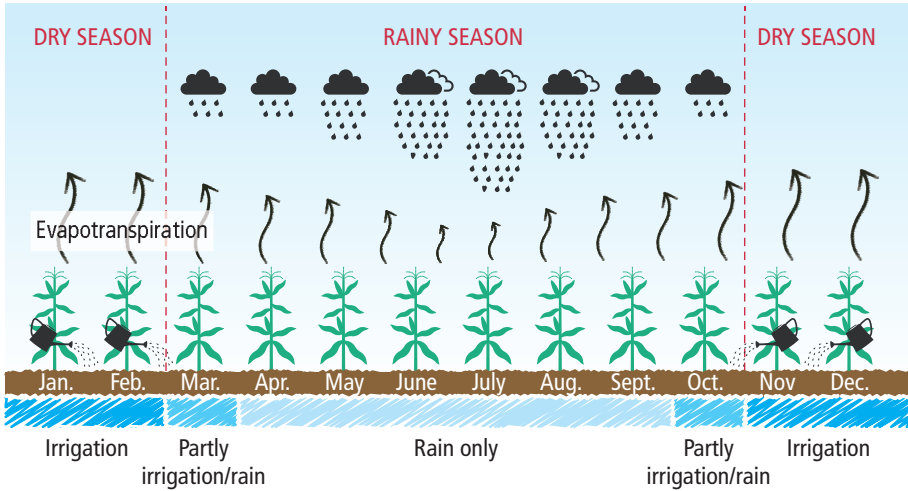
Figure 3. Generalized rainfall and irrigation pattern in subhumid and moist subhumid areas (from FAO http://www.fao.org/docrep/S2022E/s2022e06.htm).

can be in great excess of evapotranspiration, resulting in conditions that may be too wet for some crops.

A wide range of crops is grown in the subhumid zone including maize (*Zea mays* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), sorghum (*Sorghum bicolor* L.), peanut (*Arachis hypogaea* L.), food legumes, and vegetables. The names of selected crops frequently grown in these regions and associated ET values are listed in Table 1.

Intercropping multiple species is common in subsistence farming systems in the subhumid zone. These systems make more efficient use of sunlight (Keating and Carberry, 1993) nutrients (Morris and Garrity, 1993), and water (Morris and Garrity, 1993) than monocrop systems with limited inputs. Steiner (1984) reported that traditional intercropping systems cover over 75% of the cultivated area in Africa. The principal reasons for farmers to intercrop are flexibility, profit, resource maximization, risk minimization, soil conservation and maintenance, weed control, and nutritional advantages (Norman, 1974). Intercropping systems also allow farmers to maximize returns to limited resources, provide food and potential income over time, and maintain soil fertility in low input systems. These systems may involve as many as six species but more commonly feature two to three crops in a mixture that complements one another in growth habit, maturity and nutrition (Okigbo and Greenland, 1976).

In commercial systems, the move away from hand labor for planting and weeding has dictated a move to monocrop systems. Reduced cropping system complexity has allowed effective management over larger areas, provided fertility is maintained and proper rotations are implemented. This system is typified by wheat: rice rotations in India and maize:soybean (*Glycine max* L.) in North and South America.

Table 1. Seasonal crop evapotranspiration (ET) for selected crops (adapted from Burman *et al.*, 1981).

Crop	Seasonal ET (cm)
Alfalfa	60-150
Banana	70-170
Beans	25-50
Citrus	65-100
Coffee	80-120
Maize	40-75
Cotton	55-95
Cowpea	20-35
Onion	35-60
Peanut	45-70
Potato	35-63
Rice	50-95
Sorghum	30-65
Soybeans	45-82
Sugarcane	100-150
Tomato	30-60
Vineyard	45-90
Wheat	40-85

Soil loss is a major concern in this zone in both commercial and subsistence farming systems. Relatively high rainfall intensity storms often subject soils to leaching and erosion, resulting in reduced productivity, especially when cropping is continuous or fallow periods are short (Lal, 2001). In subsistence systems, crop residues are often important for animal feed, and almost all crop residues are used in this way. This precludes the use of residues for soil cover and also for returning organic material to the soil unless manure is concentrated and then applied to the crop fields. Increased residue production, via improved crop nutrition, means that more can be left on the soil for cover. Crop residue returned to the soil can improve the tilth, moisture-holding capacity, and resilience of the soil system (Karlen *et al.*, 1994). Retention of crop residue has also proven valuable in commercial farming systems through higher yields (Wilhelm *et al.*, 1986). Increased water infiltration and water-holding capacity are additional advantages in these no-tillage production systems. This increase in soil water often results in higher summer crop yields and/or greater profitability in subhumid areas such as the mid-Atlantic USA (Roygard *et al.*, 2002), northwest India (Acharya and Sharma, 1994), and southern Brazil (Machado and Silva, 2001).

Humid zones and cropping systems

Humid continental climate zones have warm-to-hot summers and cold winters. These areas are more prevalent in the northern hemisphere (mostly above 40° N latitude) than in the southern hemisphere and have precipitation that is either distributed generally equally over all months or reduced in winter months (Hess and McKnight, 2011). Summer rainfall patterns are often associated with thunderstorms. Most of North Korea, South Korea, Northeast China, and the Midwestern United States are classified within this zone (Hess and McKnight, 2011). Alfisols and mollisols are the most common soil types (Awiti *et al.*, 2007). Native vegetation in this climate zone is generally represented by hardwood forests and grasslands. Because of the occurrence of soils that hold moisture and nutrients along with generally adequate rainfall, overall, this climate zone has very high agricultural productivity potential.

Humid subtropical climate zones are generally located between latitudes 25° and 40° north and south and are most frequently on the southeastern side of continents (Hess and McKnight, 2011). Some examples include southeastern China, Paraguay, Uruguay, the southeastern United States, Taiwan, Vietnam, South Korea, Malawi, Tanzania and Zambia. Winters are cool to warm and summers are wet and warm. Significantly precipitation occurs in all seasons with summers bringing thunderstorms and, in some locales, tropical storms, hurricanes, or cyclones. Ultisols are the dominant soil type of this climatic region (Awiti *et al.*, 2007). These red and yellow soils are often less fertile than those in temperate zones because abundant summer rainfall leaches mineral nutrients below the effective rooting zone of crop plants (Lal, 2001). Resupplying these nutrients via fertilizers is an essential component of sustainable cropping systems. Without fertilizers or extensive rotations/fallow periods these soils can support crops for only a few years before nutrients are depleted and crop productivity suffers dramatically.

Main causes of water limitation in crop production in subhumid zones

Soil water interception and partitioning

The distribution of rainfall among transpiration, soil infiltration, deep percolation and evaporation is site-specific and is affected by many factors (Figure 4).

Runoff and soil loss will depend on soil types and erodibility, land form, and management systems (Lal, 1980) and can vary in the extreme among sites.

The main biophysical determinants of how rainfall is partitioned over land are detailed in Table 2. At the first partitioning point, surface runoff is influenced by soil surface conditions, soil properties, and vegetation factors such root length and density, canopy cover, degree of litter fall, seasonality of vegetation, and the impact of vegetation on the soil microbiology (Falkenmark and Rockström, 2005).
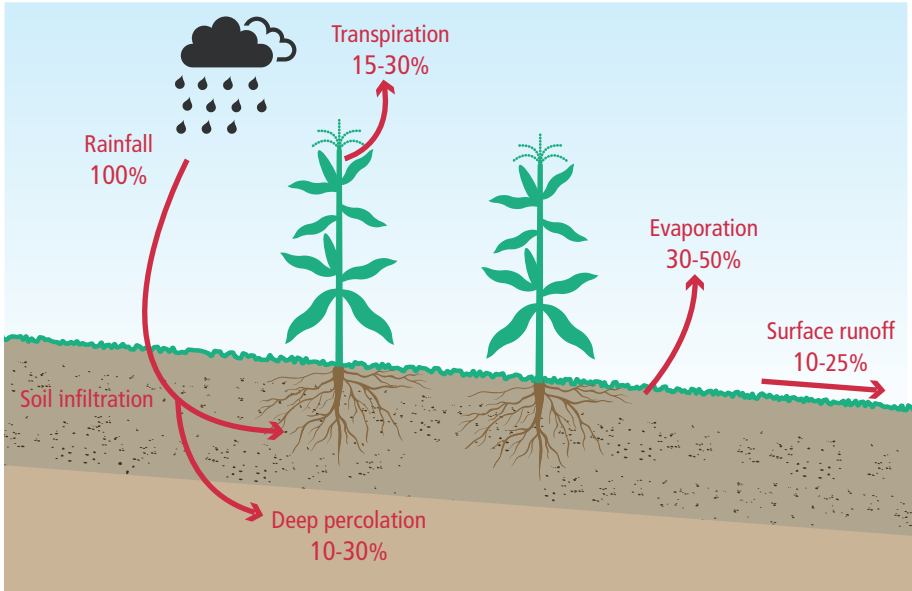
Figure 4. Rainfall partition under the savannah conditions.

Table 2. Biophysical and human factors that determine the partitioning of water flows in the hydrological cycle (adapted from Falkenmark and Rockström, 2005).

Flow	Biophysical determinant	Human determinant
1st partitioning point		
Surface runoff	Vegetation/Biomass	Land use
	Soil surface conditions	Tillage practices
	Rainfall intensity	
	Soil wetness	Soil management
	Water-holding capacity in soil	Soil management
2nd partitioning point		
Evaporation	Atmospheric demand (potential evaporation)	Canopy cover
	Micrometeorology	Mulching
	Wetness of soil	Timing of planting
Transpiration	Photosynthetic pathway	Crop management
	Plant available soil moisture	Forest management
	Atmospheric demand	
Groundwater recharge	Soil hydraulic conditions	Compaction
	Geological conditions	Cultivation management (plowing)

At the second partitioning point, soil, climatic and vegetation factors interact to control the partitioning between green water flow (evapotranspiration) and deep drainage. Because of its effects on the biophysical determinants, land management has a primary influence on rainfall partitioning. Organic and inorganic fertilization will also directly affect crop growth, and thereby change the proportion of soil-water taking the productive path of green water flow path (Hatfield *et al.*, 2001). Covering the soil surface with growing vegetation or dead crop residue, so-called mulch, creates a shaded and humid microclimate close to the soil surface and reduces evaporation from the soil. Tillage can also be used to reduce the capillary rise from the soil. Growth of vigorous, ground-covering plants is one of the most effective ways of reducing non-productive green water flow (Falkenmark and Rockström, 2012).

Partitioning of rainfall

In many parts of humid and subhumid zones rainfall is highly erratic and falls as intensive convective storms with high rainfall intensity and extreme spatial and temporal rainfall variability (Rockstrom, 2000). The result is a high risk of intra-seasonal dry spells. Such short periods of water stress can have a disproportionate effect on crop yields if they occur during water-sensitive development stages such as during flowering or yield formation (Claassen and Shaw, 1970). If actual green water flow is only half the maximum green water flow, yields will drop by at least an *equal relative* amount and be reduced to half the maximum yield, (Falkenmark and Rockström, 2012). When plant water uptake falls to 70% of maximum uptake, plant growth is affected due to soil moisture stress.

Erratic and intense rainfall can also affect nutrient losses, especially N. Flooded soil conditions result in N losses via denitrification, while N leaching is generally increased with greater water flow through soils (Havlin *et al.*, 2005). An example of the effect of extreme rainfall on N leaching is reported by Jacks and Sharma (1983) in India. These authors found that overall N losses to groundwater from fertilization were low; however in a year with a prolonged dry season, followed by heavy monsoonal rains, leaching losses were equal to approximately 25% of fertilizer N applied.

Improving water use efficiency to enhance fertilizer efficiency

Bouman *et al.* (1999) propose four objectives or approaches to improve the efficiency of crop water use and total crop production. These are:

- Increase transpirational crop water productivity.
- Increase the storage size of available water in space or time.
- Increase the proportion of non-irrigation water inflows.
- Decrease non-transpirational water outflows.

Overall strategies most important in humid and subhumid areas are likely those that capture water that would otherwise escape the plant root zone and develop it for use by crops (tolerance).

There are two main avenues for mitigating poor rainfall partition and agricultural dry spells: 1) increase the water uptake capacity of plants; or 2) increase availability of water to plants. Even though these strategies focus on water, the approaches and practices to achieve them are not restricted to water management. Partitioning of rainfall and uptake of soil water by plants are good performance indicators for all land management practices and crop and soil management can improve water uptake capacity (Table 3).

Table 3. Strategies for improving rain-fed agriculture through integrated soil and water management (adapted from Falkenmark and Rockström, 2005).

Strategy for upgrading	Management	Methodology	Target parameter
Plant water- uptake capacity	Soil management	Tillage	Root length and density
		Crop rotation	Crop development
		Mulching	
		Organic manures/fertilizers	
	Crop management	Crop choice	
		Inter-cropping	
		Timing of operations	
		Pest management	
Plant water availability	Soil management	Tillage	Soil infiltrability
		Soil and water conservation	
		Mulching	
		Crop rotation	
		Organic manures	Water-holding capacity
	Water management	Water harvesting	Dry spell mitigation

Reducing surface runoff and increasing infiltration

If rain falls on a soil surface at a greater rate than the infiltration rate, the excess water will start to collect at the surface, and when the surface storage is exceeded, or when soil is saturated, runoff occurs. There are two basic ways runoff can be minimized: 1) increased surface storage through increased soil surface roughness via tillage or surface coverage or 2) increased infiltration. Rain-fed agricultural systems in the humid and subhumid zones are particularly suitable for cover crop mulch systems because of typically adequate rainfall (Erenstein, 2003).

There are conditions where one should avoid increasing infiltration, specifically:

- On sandy soils, where under heavy rains very high infiltration rates will increase leaching and deep drainage.

- On shallow soils with limited water-holding capacity where increased infiltration can cause waterlogging and result in denitrification.

Reducing evaporation

Once rainwater has entered the soil, crop production will be related to the amount of this soil-water used to grow crop plants. Covering the soil surface with growing vegetation or dead crop residue, a mulch, can reduce evaporation from soil by changing the microclimate (Mando and Stroosnijder, 1999). Illustrating the need to integrate water and fertility management, a study by Zaongo *et al.* (1997) in Niger reported that mulch reduced evaporation mediated loss to 28% but the water saved from evaporation was not efficiently used for biomass production (transpired by plant) unless nitrogen was added to the soil which further improved water use efficiency.

One additional strategy particularly appropriate for humid and subhumid zones is vapor shift, the act of shifting water flow from evaporation to transpiration to increase the proportion of productive transpiration flow relative to total evaporation (Falkenmark and Rockström, 2012). There are two ways of achieving such a vapor shift. The first is by reducing early season evaporation through early planting, intercropping (to rapidly develop a canopy cover), or mulching. The second is by reducing evaporation flow by increasing the crop canopy cover, thus shading the soil surface. Improved management can result in a substantial vapor shift, which is much more feasible in these areas compared to more arid zones (Falkenmark and Rockström, 2012).

Reduction of deep drainage

Reducing deep drainage is often a delicate task but can be accomplished through actions that improve soil structure and soil fertility and reduce negative effects of soil acidity, resulting in more robust crop root systems that increase plant water uptake (Gardner, 1964). Root growth parameters, including length, root thickness, and root:shoot ratio are associated with drought tolerance in both indica and japonica rice leading Champoux *et al.* (1995) to conclude that quantitative trait loci for root traits could be used to screen drought tolerance. Lynch (2013) proposes a number of phenotypic characteristics that could improve nutrient and water uptake in maize. Continued improvement in drought tolerance through root growth manipulation is expected (Price *et al.*, 2002)

Methods to enhance fertilizer use efficiency

Fertilizer nutrients and their impact on WUE

Because the standard working definition of crop WUE is Yield/Evapotranspiration (YET^{-1}), management practices that increase Y either independently from ET or with no change in ET necessarily increase WUE. Viets (1962) first described the positive effect of nutrient status on WUE for several forage and cereal crops. This synergism is due to the fact that proper soil nutrient supply improves or optimizes plant growth and yield. Balanced nutrition is key to maximizing efficient water use. All macro, secondary, and micronutrients must be present at the desirable level, otherwise yield will be limited by the absence of that nutrient. Further discussion of management and supply of fertilizer

nutrients will approach the situation as components of an overall system that will generate optimum nutrient use efficiency in humid and subhumid zones.

Integrated soil fertility management

Integrated soil fertility management (ISFM) is a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm with greater yield potential combined with the knowledge on how to adapt these practices to local conditions, aiming at optimizing agronomic use efficiency of the applied nutrients and improving crop productivity (Figure 5) (Vanlauwe, 2009). All inputs need to be managed following sound agronomic and economic principles.
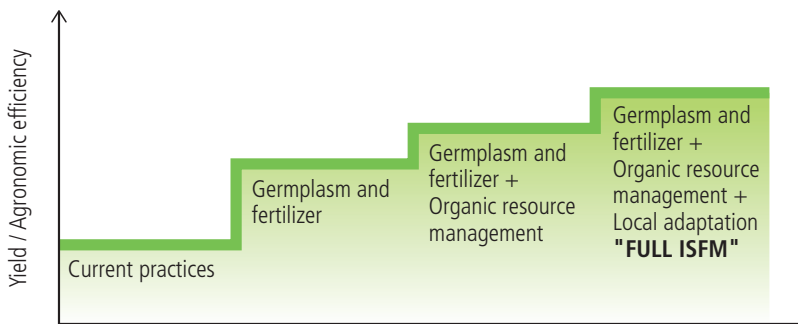
Figure 5. Illustration of components and theoretical impact of adoption of ISFM techniques and practices.

Nutrient additions

Adding fertilizer to meet crop needs can result in greater productivity per unit of water input (Cooper *et al.*, 1987). These authors reviewed the case of rain-fed cropping of cereals and food legumes in North Africa and West Asia and concluded that fertilizer to increase crop yield was one of the most important factors to achieving better water use efficiency for many crops. Similarly, improved WUE with adequate fertility is proven for wheat (Angus and van Herwaarden, 2001), and maize (Viets, 1962), in subhumid and humid zones.

The role of fertilizers in alleviation of drought stress is likely limited to cases where crops are nutrient-limited. In these situations, addition of fertilizer results in plants that are more vigorous in growth and thus more capable of using available water (Bennett *et al.*, 1989).

Nitrogen fertilizer addition typically increases plant size, root growth and total leaf area. Greater soil root exploration can result in greater water access, which effectively increases the size of the stored water pool (employing the principle of Avoidance). Rehana *et al.* (2010), working in a maize-wheat system, compared root length density of both maize and wheat in a sandy loam soil with three treatments : 1) control without any

fertilizer use, 2) N use only, and 3) N, P, and K applied as blend. They found significant increases with N addition over the control and additional, though a smaller increase when all three nutrients were supplied in both crops (Table 4).

Table 4. Inorganic fertilizer N addition effect on maize and wheat root length density in a sandy loam soil (0-30 cm) (adapted from Rehana *et al.*, 2010).

	Root length density (cm cm^{-3})	
	Maize	Wheat
Control (no fertilizer)	1.35	1.85
N$_{100}$*	1.40	2.03
N$_{100}$P$_{50}$K$_{50}$**	1.47	2.21
LSD*** (0.05)	0.02	

* N at 100 kg ha^{-1}
** N, P, and K at 100, 50, and 50 kg ha^{-1}
*** LSD = least significant difference, P<0.05.

Enhanced root growth and mass in response to added N is well documented and has also been reported in numerous crops including wheat (Belford *et al.*, 1987), barley (Brown *et al.*, 1987), and pea (Voisin *et al.*, 2006). Greater root mass, root distribution and growth improves the plants' ability to access water from deep in the soil profile and thus the total amount of plant-available water.

Similarly, as total leaf area increases, in most instances the amount of potential water transpired by the plant increases. Since increased transpiration is relatable to increased plant growth then higher yields can be achieved. In a review of nearly 100 previously published experiments, Brueck (2008) evaluated the relationship between plant biomass and WUE under variable N rate conditions and concluded that physiological, rather than stomatal, effects were more responsible for N rate effects on WUE. When N was low, plants experienced greater unproductive water losses and greater respiratory loss of carbon.

Relatively little research addressing phosphorus effects on crop WUE is available. However, a direct investigation of the impact of P supply on plant transpiration described lower transpiration (70-85%) in plants that were deficient in P when compared to the adequately supplied control (Atkinson and Davison, 1972). Relative transpiration reversed between the control and P- deficient plants after wilting. Adding P fertilizer has also been found to increase WUE of chickpea (*Cicer arientinum* L.) (Singh and Bhushan, 1980). These authors report that increased WUE in response to P fertilizer was due to both greater yield and greater use of soil water (Figure 6).

While not directly measuring overall water use, Singh *et al.* (2006) found that increased P fertility resulted in higher cotton yield, higher leaf area, and higher tissue water content in Western Australia. Similarly, a number of studies have investigated the impact of increased plant P content, as a result of mycorrhizae, on water relations
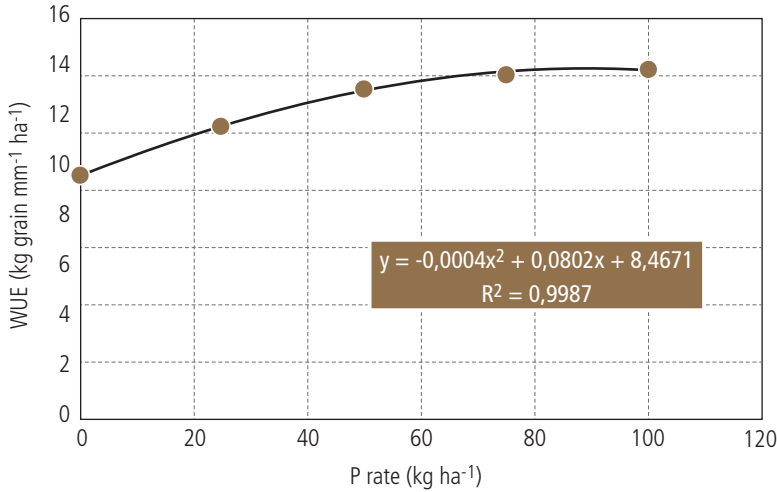
Figure 6. Total chickpea water use efficiency as affected by P fertilizer supply (adapted from Singh and Bhushan, 1980).

in durum wheat (Al-Karaki, 1998), in soybean (*Glycine max* L.) (Bethlenfalvay *et al.*, 1988), and in watermelon (*Citrullus lanatus* Thunb.) (Kaya *et al.*, 2003).

A continually improving understanding of the synergism among the various essential nutrients to optimize plant growth is needed. As an example, Blair *et al.* (1970) report that a preferential supply of NH_4-N, is more likely to enhance the uptake of P in young maize plants by lowering soil pH in the root zone, thus making P more available.

The role of potassium in plant water relations is a critical one. Potassium functions in the opening and closing of stomata, in water transport in the plant vascular system, in regulation of cell turgor pressure, and in the process of cell elongation (Marschner, 1995). Thus it is obvious that potassium plays a key role in response to water deficit. In addition to the direct impact of plant physiological functions, potassium nutrition can influence crop phenology as well. Potassium deficiency has been demonstrated to increase leaf abscisic acid level inducing premature ripening in wheat (Haeder and Beringer, 1981). Similarly, decreased leaf area and plant performance have been observed when potassium deficient conditions were observed in a forage legume in the mid-Atlantic USA (Kimbrough *et al.*, 1971) and in maize in the US Corn Belt (Heckman and Kamprath, 1992).

Nutrient placement

Fertilizer placement influences rooting distribution, but generally not the length or volume of the overall root system (Drew, 1975). However subsurface placement of fertilizer has been recommended as a tool to influence root proliferation in deeper soil zones to avoid short-term soil drying that typically occurs near the soil surface (Kaspar *et al.*, 1991). Starter fertilizer, placed in a concentrated band near the seed, can increase

early season growth and hasten maturity in many crops including maize (Vetsch and Randall, 2000) and vegetables (Stone, 2000). This encouragement of rapid early season development can carry through the entire season resulting in crops that avoid drought that occurs later in the season (Cromley *et al.*, 2006). This influence is also known to be greater in longer-season cultivars and hybrids.

Since common nitrogen fertilizers are generally water-soluble and nitrate is mobile in soil, placement of nitrogen is generally not considered critical to achieve plant uptake. Two exceptions exist. The first is the early season "starter" application effect mentioned earlier where positioning nutrients near the seed enables rapid uptake by seedlings and young plants. Delayed conversion to the mobile nitrate form has also been noted due to banding, which may decrease losses and increase the length of time N fertilizer remains available (Wetselaar *et al.*, 1972). The second case is similar in that in cropping systems where significant previous crop residue remains on the soil surface, banding N fertilizer into mineral soil reduces potential immobilization of N by soil microorganisms (Recous *et al.*, 1995). This results in a greater proportion of the applied N being immediately available for plant use. Placing urea- and ammonium-based N fertilizer below surface residue also serves to reduce the opportunity for losses via ammonia volatilization (Rochette *et al.*, 2009, Touchton and Hargrove, 1982).

Reeves and Mullins (1995) reported that deep placement of K fertilizer in cotton in the southeast USA, using subsoil tillage resulted in 10-15% lower soil water contents compared with surface application of K over two years of study with average yields of 3.2 mg ha^{-1} (Figure 7). Their study site included low subsoil K content as well as a root restrictive layer. They attributed the greater soil profile water depletion to increased root proliferation in the zone of K enrichment.
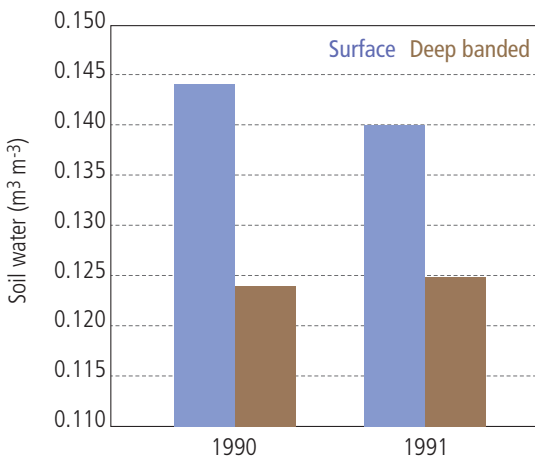
Figure 7. Effect of deep placement (40 cm) of K fertilizer via subsoil tillage on soil water content (0-80 cm) in cotton (adapted from Reeves and Mullins, 1995).

Matching nutrient availability and plant needs (synchrony)

One important key to improving N use efficiency is achieving synchrony of N delivery from soils and fertilizers and the plant's N uptake demand (Havlin *et al.*, 2005) The need to match N fertilizer supply to the time of crop demand to maximize efficiency is well known conceptually. However, achieving this ideal in practice is complicated by site-specific conditions and management decisions. Crop nutrient uptake is typically not consistent throughout the season and is characterized by relatively small amounts of nutrients early in the season, then a rapid increase as crop growth and demand increase. Nutrient uptake in response to relative crop growth in most crops can be represented using a sigmoid curve (Figure 8).
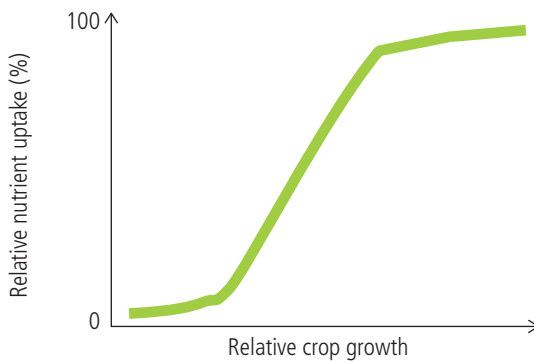
Figure 8. Relative nutrient uptake and demand in response to relative crop growth.

When soil and climatic conditions favor nutrient losses, timing N application to coincide with specific crop developmental stages can greatly increase efficiency and reduce the environmental impact of nutrient losses. For example, rice culture typically results in relatively high N fertilizer losses. In-season split application of N can greatly increase the efficiency of N as demonstrated by the work of Wilson *et al.* (1989). The authors found greater N recovery of ^{15}N-labeled urea in panicles and less N loss when N was applied 2 weeks after internode elongation. Total N recovery was reported to be 63.2, 63.3 and 70.1% for the pre-flood, internode elongation, and 14 day-post internode elongation applications, respectively (Figure 9).

In the sandy soils of the Coastal Plain region of the southeastern USA, winter wheat may receive two in-season N applications, one application at spring green-up and the other at the beginning of reproductive growth. This system results in increased grain yield and reduced lodging compared to a single spring N application (Gravelle *et al.*, 1988).

The manipulation of N fertilizer application timing to influence crop use of stored soil moisture may help improve crop productivity. Evidence of detriment effects of additional vegetative growth, stimulated by fertilizer application timing, has been documented in wheat in Australia (Dann, 1969, Van Herwaarden *et al.*, 1998). While
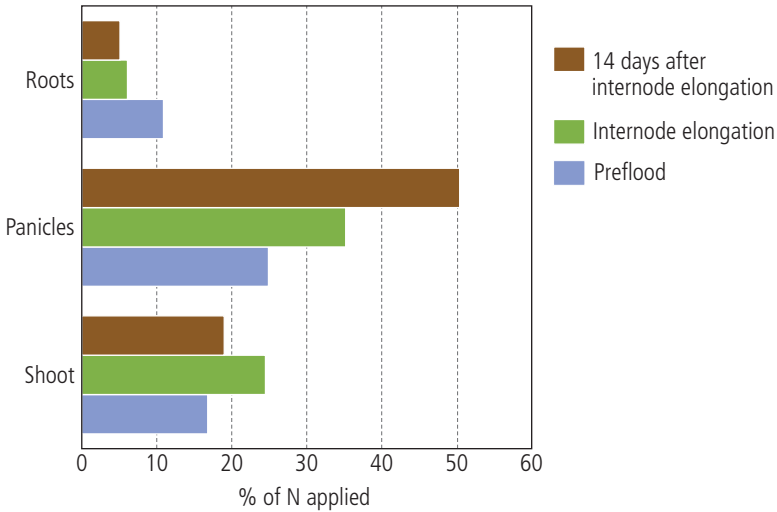
Figure 9. Fertilizer N recovered at maturity in rice plant components as influenced by N application timing (adapted from Wilson *et al.*, 1989).

this phenomenon is atypical for subhumid or humid zones, the tendency for periodic water stress does exist. So a strategy that limits preplant N supply when dry conditions persist in the early season may be advantageous. Successful implementation of this strategy will likely require that a majority of crop N is supplied in-season and that machinery and labor are available to execute this application. Using N application to maximize uptake of stored water has been shown to increase efficiency of N and water use in India (Benbi, 1990).

Site-specific nutrient management

Optimum crop fertilizer rates vary spatially by soil type (Mamo *et al.*, 2003, Oberle and Keeney, 1990), drainage (Jaynes and Colvin, 2006), and productivity; and also temporally due to variation in mineralization of soil organic matter and climate (Ma *et al.*, 1999). Site-specific nutrient management (SSNM) is an approach of supplying plants with nutrients to optimally match the inherent spatial and temporal needs for supplemental nutrients (Buresh and Witt, 2007). Experience with SSNM for rice and maize and Asia and Africa indicates that farmers achieve markedly higher financial benefits, increased yield, and optimum use of fertilizer (Buresh and Witt, 2007, Segda *et al.*, 2005)

Essential components of SSNM include:

- Indigenous soil nutrient supplying capacity.
- Uptake, recovery, and residual effects of fertilizer nutrients.
- Relationship between nutrient uptake and yield formation.
- Dynamics of nutrient demand during the cropping cycle (especially N).

- Crop management practices (land preparation methods, crop establishment methods, etc.) and production system (crop rotations, associations).
- Local financial and risk considerations (prices of inputs, such as labor and fertilizer, and produce prices; farmer purchasing power).

(Adapted from Dobermann and Cassman, 2002; Haefele *et al.*, 2003).

Incorporation of water availability into estimates of temporal and spatial N needs

Scientists and growers have long understood the relationship between crop potential and water availability in humid and subhumid climates.

Reports by Wendroth *et al.* (1999) and Zhang *et al.* (2002) among many others have illustrated the importance of including water availability and soil water-holding capacity into models that address spatial variability of N need. Other approaches have proposed to use direct, nondestructive measures from the crop canopy as a proxy for measuring general crop status that would necessarily include water supply (Holland and Schepers, 2010, Raun *et al.*, 2002) These researchers along with others (Kitchen *et al.*, 2010) have compared variable rate in-season N fertilizer with fixed rate approaches with favorable results. Timlin *et al.* (1999) found that temporal differences had a greater effect on yield than did spatial variability, mainly due to differences in weather. Combined, these types of findings highlight the importance of systems that account for variation in time (year-to-year) as well as space to increase fertilizer and water use efficiency. Improving productivity on the best soils in the best parts of fields will be one of the keys to increasing overall crop productivity in the future.

Best agronomic practices

It is important to realize that the agronomic efficiency (AE) of a nutrient is influenced by many factors other than application of fertilizer. For example, Figure 10 illustrates the compound effect of management intensity such as planting, weeding, and applying fertilizer at the optimum time on maize yield in Mali (Bationo, *et al.*, 1997).

Slow release and delayed availability sources

Slow release (SR) fertilizer N materials are used to extend N availability over a growing season and to reduce potential N losses from the soil system (Mikkelsen *et al.*, 1994). Maintaining N fertilizer availability can be achieved through various means including reduced water solubility, reduced rate of microbial decomposition, slowed diffusion through an impermeable membrane, or resin coating of the material (Hauck, 1985). These products offer potential advantages in both water and nutrient use efficiency through better matching fertilizer supply with timing of crop demand, reduced N losses from the system, and potentially greater crop yields (Shaviv and Mikkelsen, 1993). The greatest potential benefit from these SR materials in humid and subhumid areas is likely to be reduced volatilization and leaching losses, with N reductions greater than 50%
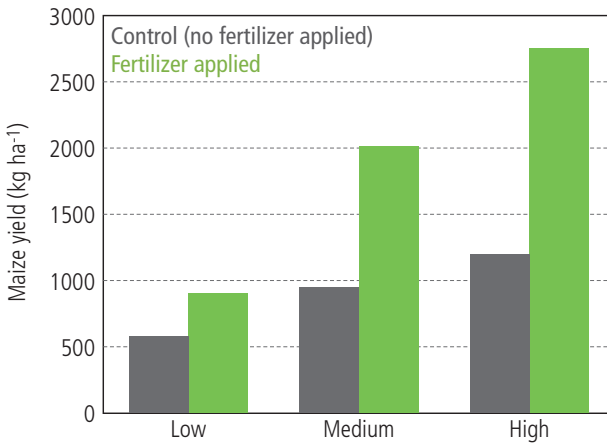
Figure 10. Effect of management practices on maize grain yield in Tinfounga, Mali (Bationo *et al.*, 1997).

when compared with some sources (Mikkelsen *et al.*, 1994). Figure 11 shows the impact of adding a urease inhibitor to urea fertilizer in a flooded rice system (Freney *et al.*, 1995).

Physical coatings or barriers that limit the availability or solubility of N fertilizer materials also show promise for increasing N uptake via better synchrony between N demand and N supply (Malhi *et al.*, 2011).

What remains to be done?

Because of the direct relationship between N need and crop yield, there will be a continual need to maintain and improve nitrogen use efficiency at similar levels of water use. Concerns over greenhouse gas emissions and the impact of N fertilizer on water quality will also be in the forefront of considerations for N fertilizer efficiency. New cultivars and hybrids that are more efficient in water and nitrogen use have the potential to dramatically change crop production in humid and subhumid areas. However, understanding the interaction of plant and trait function with environment will be a growing research challenge.

Breeding crops that more efficiently use phosphorus will likely improve WUE in situations and sites with extremely low P availability. However, managers will need to continue to supply P fertilizer to optimize crop growth in most situations so that strategies should incorporate other solutions as well.

Because of the diversity of crop and crop/livestock farming systems common in humid and subhumid areas, manure is often available for cropland application. This recycling of nutrients represents a systems approach to managing crop fertility and is
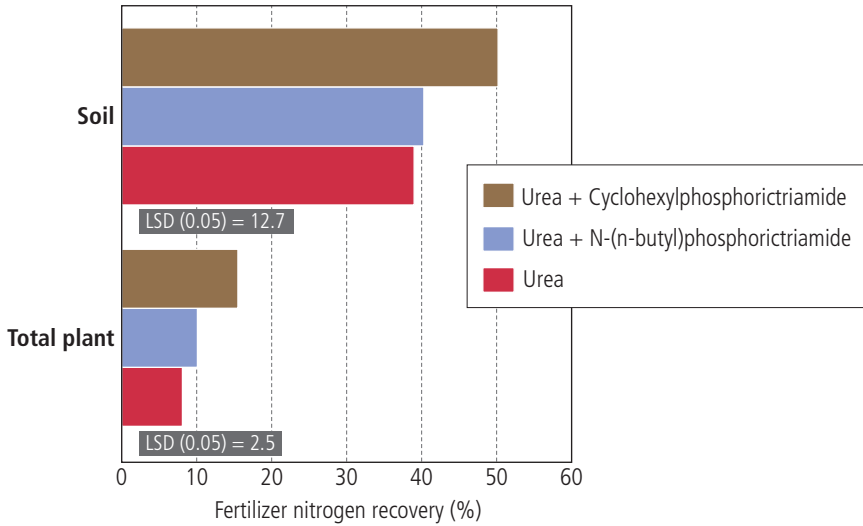
Figure 11. Rice plant and soil nitrogen recovery as influenced by urease inhibitor treatment (adapted from Freney *et al.*, 1995).

extremely useful where practical. Similarly, worldwide, a number of cities are found within these climatic zones and in many instances field application of municipal sewage sludge generated by these cities provides P (and other nutrients) for crop growth. This approach has the opportunity to grow in developing nations as sanitation and water treatment systems evolve and progress.

Higher yield potential and higher nutrient uptake demands within a similar growing season will necessitate systems that facilitate quicker nutrient and water uptake. Additional studies that investigate the most appropriate rate, placement, and timing for fertilizer supply that matches this greater demand will be essential to meeting this change in demand.

Combining techniques that increase the interception, capture and productive storage of water will become increasingly important as crop yields rise. Agronomic systems that use crop residues and/or cover crops to maintain soil cover and thus reduce evaporative losses will allow greater efficiency in the use of rainfall. Combining techniques that improve the conversion of rainfall into usable crop water with techniques that provide nutrients in the right amount, in the appropriate form and at the right time will be required in the future. Research should focus on multidisciplinary field and laboratory experiments that test fertilizers, water use and other inputs as needed to optimize crop yields.

Summary

The implications of producing adequate and desirable food for a growing population while facing the uncertain impact of climate change make improvement in the efficient use of nutrients and water essential. This is especially true in humid and subhumid regions where adequate rainfall for crop production typically occurs and as climate change influences rainfall pattern and duration. Because of the expansion in the demand for water for human use, many drier areas will face a scarcity of water available for agriculture with a resulting increased dependence on crop production in wetter areas. If available water is low, it does little good to worry about practices that increase nutrient use efficiency. To date, comparatively little research on this topic has been conducted in these humid and subhumid zones. However, improved water harvesting strategies that reduce runoff, increase infiltration, and decrease evaporative losses will capture and retain more rainfall for crop use. Combined with techniques that supply balanced fertility in an integrated system, we expect greater yields along with improved fertilizer and water use efficiency. Increased understanding of how to improve practices for higher water and fertilizer use efficiency in these areas will be needed if we are to feed the growing world population.

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Chapter 7

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

Bijay Singh[1], John Ryan[2], Con Campbell[3] and Roland Kröbel[4]

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.

[1] Punjab Agricultural University, Ludhiana, India, bijaysingh20@hotmail.com
[2] International Center for Agricultural Research in the Dry Areas, (ICARDA), Aleppo, Syria, ryanjohn1944@gmail.com
[3] Formerly Agriculture and Agri-Food Canada (AAFC), Ottawa, Canada, con.campbell@agr.gc.ca
[4] Agriculture and Agri-Food Canada (AAFC), Lethbridge, Alberta, Canada, roland.kroebel@agr.gc.ca

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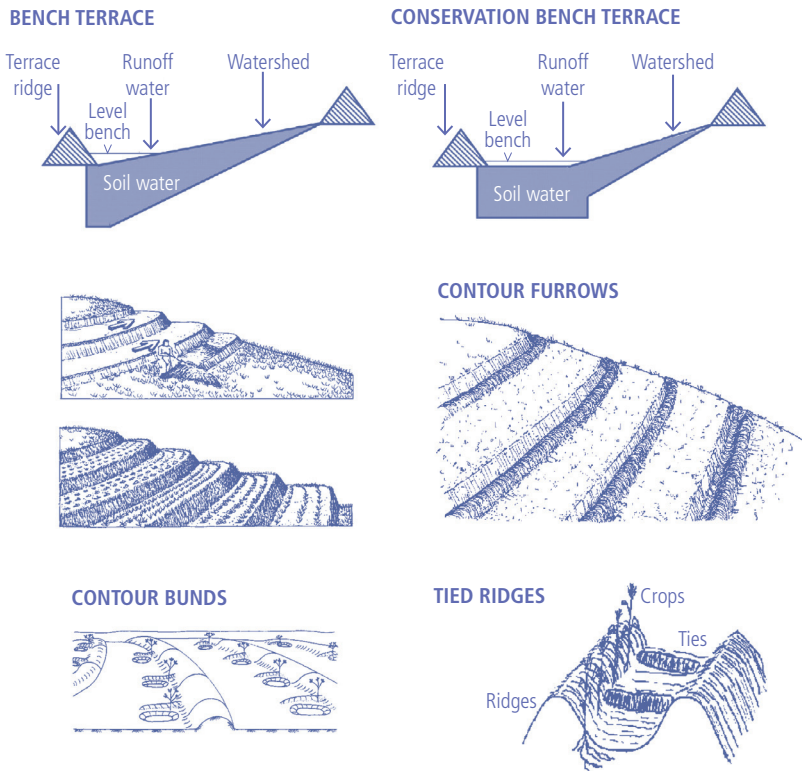
Figure 1. Different *in situ* water conservation systems followed in dry-area regions of the world.

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 *et 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 19th 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),
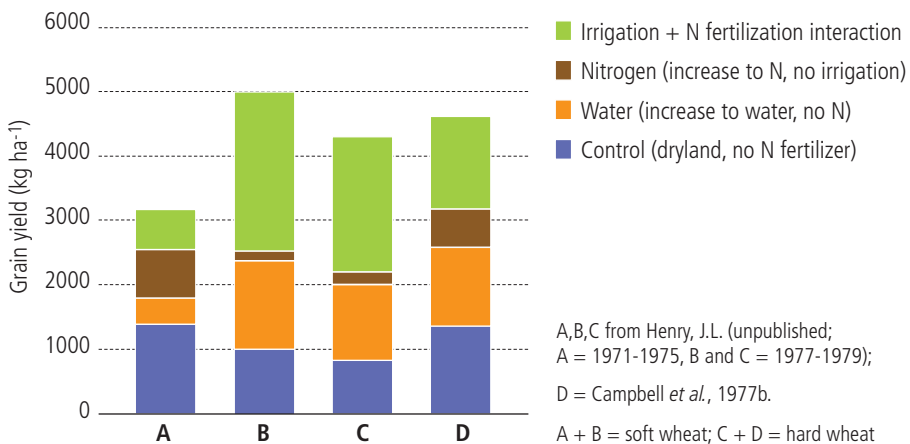

Figure 2. Effect of water, nitrogen fertilizer and their interaction on grain yield of wheat in Saskatchewan, Canada (adapted from Henry *et al.*, 1986).

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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Chapter 8

Challenges of increasing water and nutrient efficiency in irrigated agriculture

Robert L. Mikkelsen[1], Timothy K. Hartz[2] and M.J. Mohammad Rusan[3]

Abstract

The challenge of feeding a global population cannot be achieved without major improvements in both water and nutrient efficiency. Irrigated agriculture is a major user of freshwater resources and contributes significantly to food production. Simultaneous application of water and nutrients requires careful management, but offers significant potential for improved efficiency. Fertigation is well suited to achieve these goals since it can deliver appropriate amounts of nutrient and water when properly practiced. Fertigation can be done with any irrigation method that allows delivery of both water and dissolved nutrients to crops. However, uniform water distribution is important since zones of overapplication or underapplication result from nonuniform irrigation systems.

Improvements in fertilizer efficiency can be achieved by properly managing nutrient applications, including the right source of fertilizer applied at the right application rate, at the right time, and in the right place (4Rs). For example, soluble nutrient **sources** are best suited for fertigation, but a variety of less-soluble sources are excellent for soil application in irrigated conditions. Fertigation allows the **rate** of nutrient application to be easily adjusted to meet crop needs. Applying water and nutrients at the right **time** in the crop growth period is another important tool for improving efficiency. Many fertigation techniques allow water and nutrients to be **placed** closely to plant roots. Using these 4R techniques have been repeatedly demonstrated to boost crop yields while improving both water and nutrient efficiency.

[1]International Plant Nutrition Institute (IPNI), Peachtree Corners, GA, US, rmikkelsen@ipni.net
[2]University of California, Davis, US, tkhartz@ucdavis.edu
[3]Jordan University of Science and Technology (JUST), Irbid, Jordan, mrusan@just.edu.jo

Introduction

A major challenge facing the growing global population is satisfying the increasing demand for food while maintaining a healthy environment. Scarce resources must be conserved and utilized as efficiently as possible to achieve this goal. There are large areas of the world where there are opportunities to sustainably intensify agricultural production and meet the twin goals of production and resource conservation (Neumann *et al.*, 2010; Van Ittersum *et al.*, 2012).

Two of the largest factors contributing to the large yield gap between high-productivity farmers and "average" farmers are management of water and plant nutrients (Mueller *et al.*, 2012). Progress towards improving management of water and nutrients will result in increased crop yields.

Water supply and quality will continue to be major global issues as shifts occur in urbanization, sanitation, declining availability of groundwater, and increased environmental regulations. Many of these issues relate directly to agricultural water use and urban competition with crop and animal agriculture. Because irrigated crops consume large quantities of water, improved crop water use would help accomplish many societal goals (Evans and Sadler, 2008).

Irrigation accounts for more than 70% of total water withdrawals on a global basis (FAO, 2012a). The inevitable competition between agriculture and other users of limited water resources will require that farmers become more efficient at producing crops with a finite water supply. Additionally, because irrigated agriculture provides about 40% of the global food supply on 20% of the total cultivated land, the pressure to produce even more food on irrigated land will also intensify.

Much of the current irrigation water comes from surface supplies, but 40% of the irrigated area uses groundwater sources (Siebert *et al.*, 2010). Groundwater can provide a reliable source of water for irrigation and domestic use, but in many regions groundwater levels have been rapidly dropping. This excessive overdraft of water may also reduce river base flows and have negative impacts on aquatic habitat.

Treated wastewater is currently utilized for irrigation in many parts of the world to stretch limited water resources. When properly treated, this resource can be an important contributor to the agricultural water supply. As water demands increase (especially in peri-urban areas), recycled water will be increasingly used for irrigation of both edible and nonedible crops. The unregulated use of nontreated wastewater is also substantial, especially in developing countries.

Efficient water use

The critical linkage between soil moisture and crop growth is due to the large amount of water that flows from roots through the plant and is then evaporated from leaves through transpiration. Many common crops require between 300 (sorghum) and 800 (alfalfa) kg of water to produce one kg of dry matter (Chrispeels and Sadava, 2003). Major global grain crops require between 1,000 and 3,000 kg of water to produce one kg of harvested grain (Rockström, 2003).

In some environments, the proportion of water that is actually used for transpiration (green water) is relatively small (Sposito, 2013). For rain-fed crops, only a small fraction of the rain is used directly for transpiration (often from 15 to 30%) and can be as low as 5% (Rockström and Falkenmark, 2000). For irrigated agriculture, the fraction of the applied water that is used directly by plants is generally higher, but can also be low (~15%) in many conditions (Wallace and Gregory, 2002). A number of techniques can be implemented to increase the water uptake ratio.

Any improvements in water use efficiency (WUE) must be tied to gains in agricultural productivity as much as possible, but WUE should not be a target by itself. Enhanced WUE goals should be considered within a comprehensive crop production package that includes related factors such as tillage practices, nutrient management, resource conservation techniques, and pest and weed control (Hsaio *et al.,* 2007). These management practices all increase the harvested crop per unit of water added, but significant progress will occur if more grain or harvested product is grown per unit of water transpired.

Linking water and plant nutrients

The practice of providing crops with fertilizer nutrients in the irrigation water is called fertigation. When properly performed, fertigation has been consistently demonstrated to increase fertilizer efficiency and crop growth by closely controlling the rate and timing of water and nutrient delivery, compared with traditional techniques (Kafkafi and Tarchitzky, 2011). Nitrogen fertilizer is the most commonly added nutrient used in fertigation, but all plant nutrients can be delivered with fertigation with proper management. Since nitrogen is the nutrient most often required in the greatest amount and is readily susceptible to loss from the root zone with water, it is the nutrient primarily discussed in this chapter.

The close linkage between water use and nitrogen management necessitates their simultaneous management. Greater nitrogen use efficiency (yield per unit of N supplied) is often accomplished by carefully supplying sufficient nitrogen fertilizer as close to the time of plant demand as feasible. Fertigation is well suited to achieve this goal, and it can thereby minimize nutrient losses since the appropriate amount of nutrient can be applied at the correct time.

Crops that have a large yield response to nitrogen fertilization may be best suited for efficiency improvements through fertigation. This can be practically accomplished by avoiding the relatively high fertilizer rates that are sometimes applied at the time of planting or in a single mid-season application for both annual and perennial crops. The potential loss of fertilizer N (through leaching or denitrification) is greatly reduced when multiple applications are made (Figure 1).

Optimizing both water and nutrition for many horticultural crops can be challenging because both yield and quality must be considered. The concept of maximum *economic* yield is especially important for these crops. For example, a restricted supply of water and nutrients might produce a plant of moderate size, but there may be no marketable yield. Growers of high-value crops need to simultaneously balance many factors in determining the practices that will lead to maximum yield or to maximum marketable
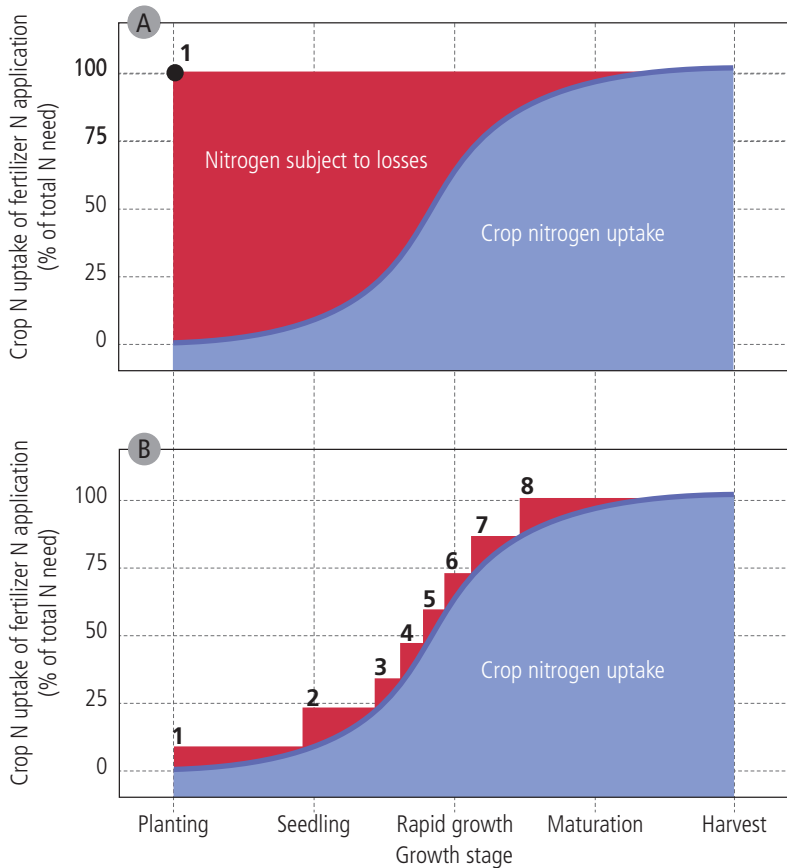
Figure 1. Example of potential N loss occurring when fertilizer is applied in a single application (A) or in eight fertigated applications (B). Inorganic N present in the soil in excess of plant demand is at risk for leaching and denitrification loss. Split applications of fertilizer will reduce the amount of N vulnerable to loss through the growing season (red shaded area) (adapted from Doerge *et al.*, 1991).

yield. Since the economic value of many of these crops far exceeds the expense of fertilizer, both of these yield goals may be similar. It is difficult to account for any adverse environmental costs associated with inefficient water or nutrient use, but these externalities need to be considered.

The use of controlled-deficit irrigation (CDI) has been gaining interest. This practice involves intentionally withholding water during specific stages of crop development to conserve water, yet still obtaining satisfactory yield and quality (FAO, 2002). This technique of deliberate water stress has been successfully implemented in a variety of crops under carefully monitored conditions. Controlled-deficit irrigation has been

most widely studied in perennial crops (trees and vines), but a significant loss of yield and vigor can occur if it is not properly performed. It is more challenging to use CDI on short-season crops without reducing yield or quality, but it can be done for some crops at the proper growth stage (e.g. Fabeiro *et al.,* 2001). Implementing CDI can complicate fertigation practices since water stress is intentionally imposed and it is decoupled from actual physiological nutrient requirements.

Uniform application of water

Uniform distribution of water within a field is an important consideration for any irrigation system. Zones of overapplication (causing leaching or waterlogging) or underapplication (inducing drought stress) result from nonuniform irrigation systems. A properly designed irrigation system can optimize uniformity, but proper management and regular maintenance are still required.

Water losses through evaporation, runoff, or subsurface leaching should be minimized as much as possible. Proper spacing of lateral lines, maintaining proper pressure, repairing leaks, and replacing malfunctioning equipment can all help maintain uniform water application. Irrigating during strong winds can also distort water distribution patterns.

Uniform water application and applying the proper rates are essential to minimize nutrient percolation losses. Any improvements in nitrogen fertilizer management can be offset by improper water use. The extent that nitrate leaching can be reduced in irrigated cropping conditions also depends on the ability of farmers to manage water to respond to changes in climatic conditions and the spatial variability of the soil. When farmers have the ability to make multiple applications of nitrogen during the growing season, their ability to reduce nitrate-leaching losses is greatly enhanced (Fageria and Baligar, 2005). Water application must also be based on the water infiltration rate and water-holding capacity of the different soils within a field.

Irrigation scheduling

While applying the right amount of water in the right place is essential for maximizing efficiency, the ability to schedule water delivery according to crop need is also an important consideration. Accomplishing this goal is not always a simple task. It involves integrating the available irrigation technology with up-to-date knowledge of the soil moisture, the water-holding capacity of the soil, current and predicted plant transpiration, and characteristics of the plant root system.

Techniques for determining the water status for a specific field range from simple methods (the "feel method" or a shovel) to sophisticated sensor networks that continually monitor moisture through the soil profile and report through a wireless network to a centralized hub. The appropriate sophistication of these techniques will differ across the globe.

Local water demands are estimated by climate conditions and the crop canopy development. A number of excellent methods have been developed to estimate crop evaporative demand or soil moisture depletion (FAO, 2012b). The application of water also needs to account for the deliberate addition of surplus water (leaching fraction)

for salinity management. Intentional leaching should primarily occur when the concentration of nitrate is low in the soil (such as post-harvest). Understanding the need for water application and then precisely delivering that amount is essential for making improvements in nutrient management.

Irrigation systems

Fertigation can be coupled to any irrigation method that allows delivery of both water and dissolved fertilizer to crops. One of the early (and still utilized) fertigation techniques is to simply allow anhydrous ammonia (NH_3) to slowly bubble into a ditch or canal before the water enters the agricultural field. This technique relies on the uniform application of the irrigation water to properly distribute the nitrogen fertilizer across the field in furrows or in a flood situation. The distribution of nutrients cannot be more uniform than the distribution of water. This system can be used for flooded paddies or for upland crops. There are ample data to show that this technique frequently results in nonuniform nutrient application, but the simplicity offers some appeal (Pettygrove *et al.,* 2010). With precision land-leveling equipment becoming more widespread, these surface irrigation methods are becoming more efficient at uniformly distributing water and dissolved nutrients.

Modern fertigation is more commonly used with pressurized irrigation systems. These may include a variety of overhead sprinkler systems (fixed, linear move, or center-pivot) and microirrigation techniques (drip and micro-sprinklers).

Overhead sprinklers

This type of irrigation includes a wide variety of equipment, including solid-set sprinklers (permanently installed), moveable sprinklers, and self-propelled systems (including rolling lateral-move systems and center-pivot systems). Since these systems apply water to the entire area, they are prone to relatively high evaporative loss and possible off-target applications.

Sprinkler techniques generally provide a more uniform distribution compared with surface irrigation techniques (such as flood or furrow). With proper design and system maintenance, application efficiency can be 0.9 or higher (Howell, 2003), but windy conditions often hinder achieving this potential.

The most common irrigation systems in the U.S. are self-propelled center-pivot and linear-move rolling sprinkler systems. These systems are popular because they can rapidly cover a large area, do not interfere with field operations, and have lower maintenance costs than microirrigation systems. They are well suited for large fields and can be adapted for site-specific variable water and nutrient delivery by accelerating or slowing the rate of delivery, or with nozzle controllers.

The center-pivot irrigation system rotates around a fixed pivot point. The length of the total span can range from 60 to 800 m. The water delivery rate of the sprinklers is adjusted across the span, increasing with distance from the pivot point. Center pivot

systems can have good uniformity in proper conditions, with a typical uniformity coefficient between 0.7 and 0.9 (Palacin *et al.,* 2005).

Overhead sprinkler systems are easily adapted for adding chemicals and nutrients, but the high volumes of water relative to the added fertilizer make a relatively dilute solution. Thus fertigation is not an effective way to deliver foliar fertilizers. Most of the nutrients applied through fertigation are washed from the leaves and then enter the soil (Sumner *et al.,* 2000).

In sprinkler irrigation systems, nutrient applications generally maintain a constant concentration of soluble fertilizer in the water. It is possible to apply more or less of the fertilizer-containing water to the field in order to achieve a variable rate of application, but this also results in a variable rate of water application (King *et al.,* 2009). A center pivot system that has independent control of water and fertilizer is ideal for maximizing both water and fertilizer use. There are systems in development that provide both fertilizer and water application though separate delivery lines in one irrigation system.

When irrigating large fields (60 ha is common for center pivot), the range of existing soil conditions in a single field can cause suboptimal water application. For example, variations in infiltration rate, water-holding capacity, subsurface conditions, and topography can all cause the improper amount of water and soluble fertilizer to be applied with a single uniform application rate.

Adapting site-specific techniques for overhead irrigation systems to improve water use can be as simple as not overirrigating in areas of the field that are inherently drier (sandy soils), avoiding over application on hillsides to avoid runoff, and proper sprinkler head selection to match the irrigation design.

Further adjustment of the water flow has been demonstrated with the control of end guns, controlling the start and stop points, and modifications in the sprinklers (such as LEPA, bubblers, sprayers, and spinners). Given the degree of automation that many center-pivot systems use and the large coverage area with a single pipe, there is potential for further improvements in site-specific water and nutrient application with this type of irrigation system (Evans *et al.,* 2013).

Drip irrigation

The rapid adoption of microirrigation in agriculture has been largely due to the efficiencies from more precise delivery of water. But the advantages of simultaneous delivery of water and nutrients are also widely recognized. The multiple benefits of fertigation compared with broadcast applications of fertilizer have been reported by many researchers (Agostini *et al.,* 2010). However, the majority of crops are still irrigated using surface or sprinkler techniques.

A wide variety of drip/trickle irrigation systems have been developed. The central concept is the delivery of water at a fairly low application rate (~2 to 8 l hr^{-1}) close to plant roots, with only partial wetting of the soil, in synchrony with transpiration demands, with a minimum of evaporation loss from the soil surface, and minimal deep percolation. The application efficiency for drip irrigation can be as high as 0.9, compared to 0.6 to 0.8 for sprinkler and 0.5 to 0.6 for surface irrigation (Dasberg and Or, 1999; Simonne *et al.,* 2007).

Drip irrigation also allowed crops to be grown on land that was not previously feasible to irrigate due to sloping terrain. There are numerous examples where farmers were able to double their irrigated land when moving from flood to drip systems (e.g. sugarcane farmers in Maharashtra, India).

The desire to conserve water and reduce labor costs was the primary motivation for early adoption of drip irrigation, but improved crop yields and quality have subsequently become important factors for adoption Drip irrigation will continue to replace surface irrigation in situations where water supplies are limited and costly, or when there is competition between urban water users and farmers and the increased yield and quality offset the added costs. Even in less-developed countries, the use of drip-irrigation techniques is being rapidly embraced as a way to meet multiple crop production goals.

Drip irrigation has an additional advantage in that it is easier to maintain a proper balance between soil water and soil aeration. With furrow and flood irrigation, the soil may become temporarily waterlogged, thereby reducing the oxygen supply to plant roots. The excess water that inevitably drains from the soil carries valuable plant nutrients (such as nitrate) with it.

Changes in the delivery of water to crops will impact plant root distribution in the soil. When a larger volume of soil is irrigated, a larger root system typically develops. When drip-irrigation directs water to a limited volume of soil, the highest root density develops in a localized region near the water source (Araujoa *et al.,* 1995; Zotarelli, Scholbeg *et al.,* 2009. This restricted root system is not a problem for plant growth as long as favorable soil conditions are maintained (e.g. low salinity, adequate aeration, and proper soil chemical and physical properties).

Drip systems require regular monitoring and maintenance to sustain their high efficiency. Leaks can develop from mechanical damage and emitters can become plugged, even with extensive water filtration. Salt accumulation can occur at the edge of the wetting front in the soil, so salinity buildup needs to be monitored. The soil wetting patterns achieved by drip systems may not be sufficient to germinate seeds, thus supplemental irrigation during the establishment phase of some crops may be required.

Subsurface drip irrigation

Installing the drip system beneath the soil surface further limits evaporation from the soil and allows delivery of water and nutrients directly to the root zone. Simultaneous delivery of water and nutrients directly to roots has been shown to be advantageous for a variety of crops (e.g. tomatoes: Hanson and May, 2004; Hartz and Bottoms, 2009), while minimizing nitrate-leaching losses (Figure 2).

Since subsurface drip irrigation (SDI) can restrict the size of the root system to the wetted volume of soil (e.g. Bravdo and Proebsting 1993; Fereres and Soriano, 2007), it is essential to maintain a continuous supply of moisture and nutrients during the entire growth cycle. The spacing and location of SDI lines can also be important during the germination and seedling phases of production. Adoption of SDI may require changes to some field operations, such as tillage, but SDI systems can be used for several consecutive years.
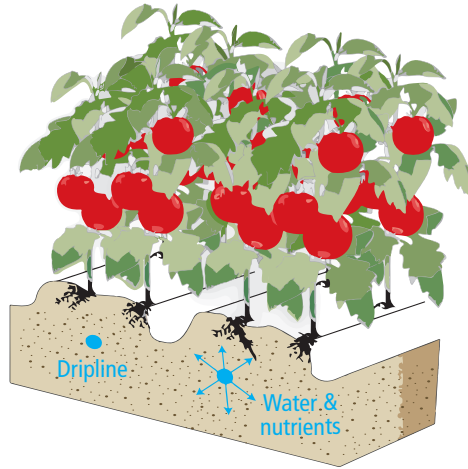
Figure 2. The use of subsurface drip irrigation delivers water and nutrients directly into the root zone. With careful management, this technique can result in enhanced resource efficiency, improved crop yields, and better harvest quality.

Micro-sprinklers

The use of micro-sprinklers has become common for irrigating perennial crops. There are several types of small sprinkler heads that spray water in various patterns. Flow rates are generally in the range of 10 to 100 l hr^{-1}. They are best suited for irrigation of perennial crops, where the root system develops for many years.

The wetted area of micro-sprinklers is much larger than with a drip emitter, providing a greater soil volume for exploration by the root system. This wider wetting pattern can be especially important in a coarse-textured soil where lateral water movement is limited. Micro-sprinklers have a higher water application rate than drip systems, but the duration of an irrigation event is usually shorter, providing some flexibility in management.

Micro-sprinklers spray water into the air, so evaporation losses can be somewhat higher than with drip or SDI systems. Since water application rates are greater with micro-sprinklers, equipment costs (pumps, filters, pipes) may also be initially more expensive, compared with drip systems.

Successful fertigation

Simultaneous application of water and plant nutrients offers many potential benefits for improved plant growth and enhanced efficiency of water, fertilizer and labor. However, a greater degree of training, experience and management is required. The lack of technical support is a barrier to greater adoption of this method of fertilization in many regions.

The selection of specific nutrient sources for use in fertigation must take into account the design characteristics of the irrigation system, the chemical properties of the

irrigation water, the characteristics of the specific fertilizer (such as solubility, reactivity and purity), and nutritional needs of the plant (IPI, 2008).

Fertilizers applied with irrigation water must be soluble in water and must not chemically react with the irrigation water and form precipitates that can clog irrigation equipment. A variety of excellent soluble nitrogen sources are available for fertigation. Potassium fertigation is relatively simple since it is not excessively mobile, except in sandy soils, nor is it subject to complex chemical reactions in the soil or water. Phosphorus application with irrigation water is more complicated since many phosphorous fertilizers are not readily soluble, have limited mobility in soil, and rapidly form insoluble precipitates with calcium and magnesium in irrigation water (Mikkelsen, 1989). Nonetheless, there are many growers who successfully fertigate with phosphorus by paying close attention to these issues.

The selection of a specific irrigation system for fertigation will also influence plant nutrient recovery. For example, Edstrom *et al.* (2008) applied various potassium sources through three irrigation systems to almond trees. They found that potassium applied via micro-sprinklers had the largest recovery by the trees, followed by a dual tube drip system and then a single drip tube. They attributed these differences to the volume of wetted soil beneath the trees.

Nitrogen management

Nitrogen use efficiency can be improved by carefully supplying inorganic nitrogen as close to the time of plant demand as possible. Fertigation is well suited to achieve this goal, and simultaneously minimizes nutrient losses through leaching (Mohammad *et al.,* 2004). This approach avoids having a surplus of inorganic nitrogen in the soil at any given time that might be at risk for unanticipated leaching loss (Obreza and Sartain, 2010). The linkage between water management and nitrogen management demands careful management of the two together. Crops that have a fairly large nitrogen requirement may be best suited for improvements in efficiency through fertigation by avoiding the relatively large fertilizer applications that are typically applied at planting or in a single mid-season application.

Nutrient management with the 4R's

A large improvement in nitrogen efficiency can be accomplished by properly managing nutrient application; using the right source of fertilizer, applied at the right application rate, at the right time, and in the right place (4 Rights; 4R). The application of the 4R principles of nutrient stewardship is relevant in all situations where fertilizers are used for crop growth (IPNI, 2013).

The ultimate fate of soil nitrogen depends on many factors including the fertilizer source, the application rate, the water management, crop uptake, microbial processes, and the leaching potential of the soil. Since nitrate is soluble, it tends to move to the edge of the wetted soil; therefore, strategies that limit the wetted volume and avoid application of excess water can minimize nitrate-leaching losses.

Right source

Fertigation provides targeted nutrient delivery to crops, but the behavior of the appropriate fertilizer source must be understood. For example, a commonly used fluid nitrogen fertilizer (urea ammonium-nitrate; UAN) provides half of the total nitrogen from urea, one quarter from ammonium, and one quarter from nitrate. Adding this soluble fertilizer during the early phase of an irrigation event can cause the nitrate and urea to leach beyond the root zone. Applying the UAN fertilizer late in the irrigation cycle can result in poor distribution in the soil and leave nitrogen remaining in the irrigation line where it can promote system-clogging algae growth (Hanson *et al.,* 2006b).

Hanson *et al.* (2006a) reported that a fertilizer solution of UAN was best distributed through the wetted soil when it was added to the irrigation with the water during the middle 50% of the irrigation cycle in drip irrigation. For buried drip systems, they recommended that application of the UAN fertilizer near the end of the irrigation event allows urea and nitrate to accumulate in the zone of greatest root density. Ammonium had the least initial mobility from the drip emitter, compared with urea and nitrate (Figure 3).

Right rate

In-season fertilization rates can be refined by using various simple (e.g., leaf color charts) or sophisticated analytical monitoring tools. For example, electronic sensors can track soil nitrate concentrations and plant tissue status, thereby allowing growers to refine nitrogen application. Schepers *et al.* (1995) demonstrated that fertilization rates of maize could be adjusted by tracking crop needs with a chlorophyll meter to schedule nitrogen fertigation through center-pivot systems. They reported that fertilizing according to chlorophyll meter readings allowed a savings of 168 kg N ha^{-1} in the first year and 105 kg N ha^{-1} in the second year without reducing yields (compared with standard practices). The adoption of these sensor-based technologies can be profitable compared with nonprecise fertilizer application, depending on crop and fertilizer prices (Biermacher *et al.,* 2009).

Nutrient budgets (tracking inputs and outputs) are a convenient way to monitor progress towards achieving the right rate. Budgets only account for the rate of application, which can lead to misleading conclusions regarding nutrient stewardship. Although budgets are useful indicators of system improvement trends, an overreliance on budgets alone will fail to account for improper combinations of nutrient source, rate, time and place. Management of water and nitrogen requires an integrated approach to make significant progress towards improving overall efficiency.

The critical aspect of applying the proper amount of irrigation water dominates many of the fertilizer decisions. Obreza and Sartain (2010) remind growers that although fertigation is often called "spoon feeding", excessive irrigation will still move the added "right amount" of nitrate beyond the root zone if water is applied in excess. It is recognized that a large quantity of dry nitrogen fertilizer on the soil surface may be subject to various losses during an intense rainstorm. However, the same quantity
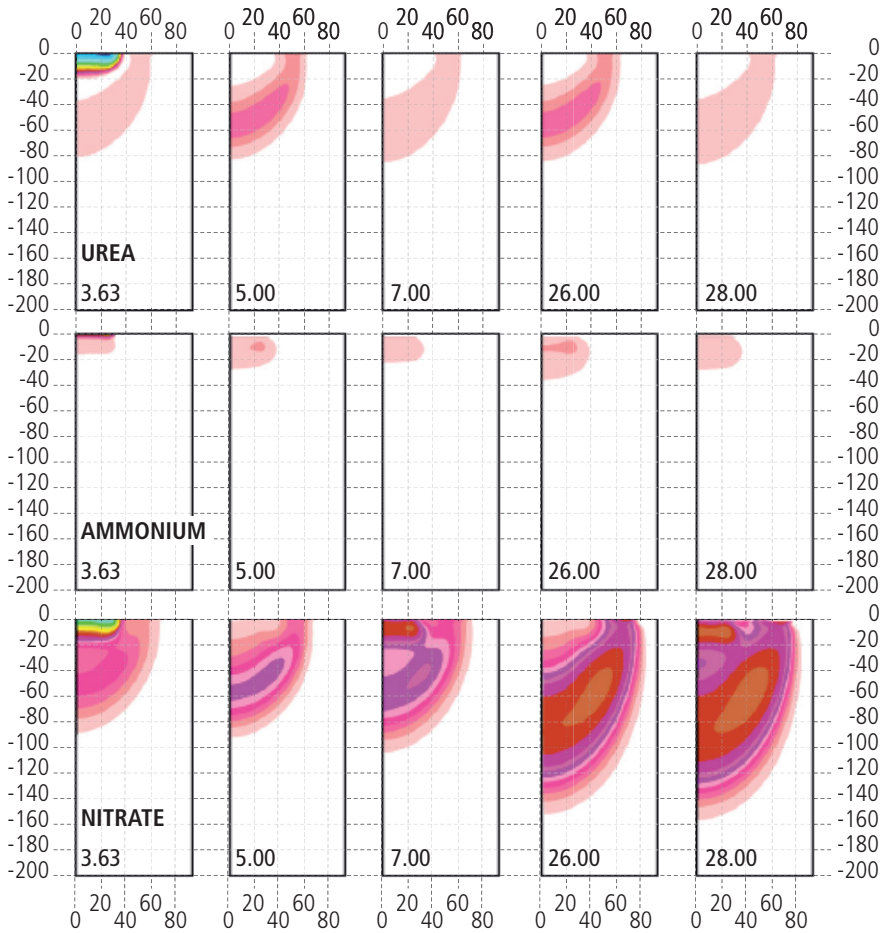
Figure 3. The spatial distribution (cm) of urea, ammonium, and nitrate fertilizer in the soil with time (up to 28 hours) following application from a drip emitter (upper left corner) (adapted from Hanson *et al.*, 2006a).

of nitrogen fertilizer could be lost in frequent small doses through fertigation if excess water is repeatedly applied with poor management.

Right time

The ability to apply multiple small increments of nitrogen during the growing season can reduce the risk of nitrate loss from excessive irrigation or during rain events (e.g. potatoes; Westermann *et al.*, 1988). Matching the timing of fertilizer application with the plant requirement (Figure 4) can also boost crop yield and quality (e.g. potatoes; Lauer, 1985). Fertigation capabilities allow growers to quickly respond with proper timing of nutrient application that is synchronized with crop demand. They can also
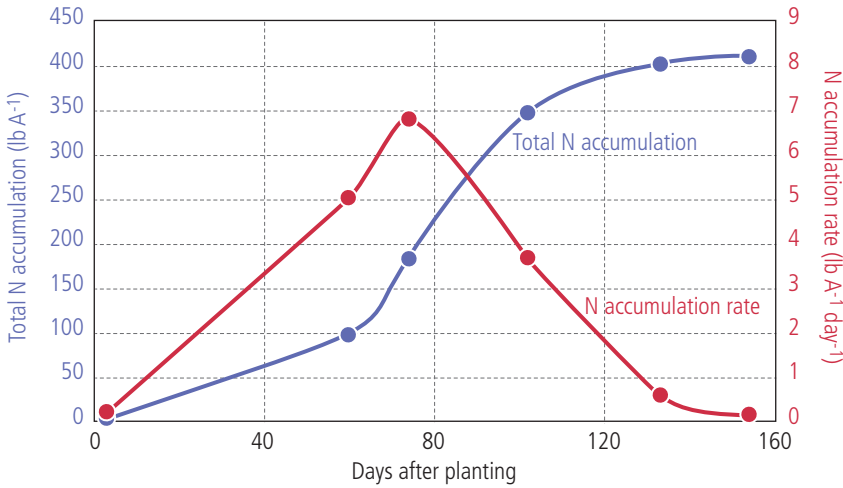
Figure 4. The rate and total accumulation of nitrogen by irrigated potato (Horneck and Rosen, 2008). Knowing that nitrogen accumulation peaks at 70 to 80 days after planting in this environment serves as a guide for fertigation practices.

respond to changes that occur during the growing season and to unforeseen nutrient deficiencies.

For example, a 3-year study of irrigated crops grown between the French Alps and the Rhone Valley demonstrated that crops did not effectively use 30% of the added nitrogen. This inefficiency was primarily attributed to improper timing of application, where nutrient applications were not properly synchronized with crop demand (Normand *et al.,* 1997).

Fertigation offers benefits of more flexible timing in nutrient applications in response to growing conditions. While no advantages are typically observed with daily fertigation compared with weekly fertigation (Simonne and Hochmuth, 2007), nitrogen applications can be easily modified to meet plant demand or adjust for weather-related variables (such as unexpected rainfall or temperature extremes).

Nitrogen applications should be delivered to match crop growth and nutrient demands. For example, with many cool-season vegetable crops both growth and nitrogen uptake are slow during the first half of the cropping period (Figure 5). During the second half of the growing period (rapid vegetative growth), the nitrogen uptake rate increases and it may reach a demand of 3 to 5 kg N ha^{-1}day^{-1} (Pettygrove *et al.,* 2003).

Many plants have the ability to accumulate more nutrients than are needed at a given time (luxury consumption) and then remobilize the nutrients later in the growing season. This accumulation provides some flexibility in timing so that nutrient delivery practices do not need to be excessively complicated.

Cumulative N uptake (% of seasonal total)

N uptake rate (lb A^{-1} day^{-1})
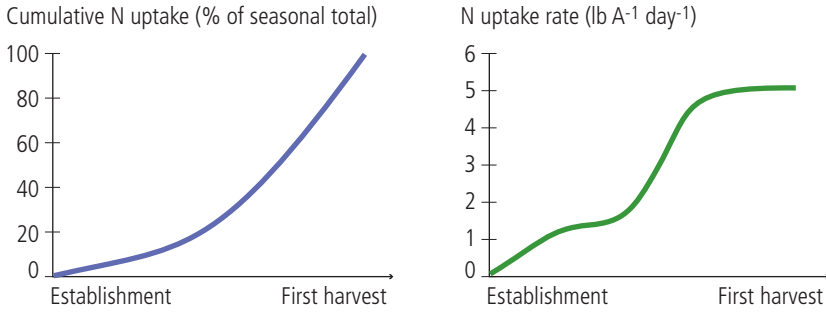
Figure 5. The seasonal pattern of nitrogen uptake (cumulative and daily) by cool-season vegetables in California (adapted from Pettygrove *et al.*, 2003).

Right place

Placement of nutrients near the root zone is also an important practice for improved efficiency (Fageria and Moreira, 2011). Proper placement can be especially important with shallow-rooted crops where excessive irrigation can easily move soluble nutrients beneath the root zone.

Root systems tend to proliferate where sufficient water and nutrients exist in the soil. For example, Zotarelli and Scholberg *et al.* (2009) reported that the largest concentration of tomato roots was found near the soil surface in proximity to the SDI line with fertigation. Applying water and nutrients so that they are positionally available to the roots is fundamental to enhancing efficiency.

Monitoring water and nutrients

Since it is not practical for farmers to measure nitrate movement through the soil profile during and following irrigation events, documenting improvements in efficiency is difficult. Researchers commonly use intensive soil sampling, soil solution extraction, and lysimetry to measure nitrate movement, but these tools are not practical for most farmers.

Given the complexity of monitoring the crop, soil conditions, and the water supply, a variety of computer programs (including crop development models and decision support systems) have been developed to guide farmers to profitability while maintaining minimal environmental impact. These relatively simple modeling tools provide useful guidelines for improved water and nutrient management.

It has been well established that using evapotranspiration (ET) as a guide to irrigation scheduling can help avoid misapplication of water. An increase in nitrate leaching is inevitable when water is added in excess of ET. There are several successful approaches

for determining ET and using appropriate crop coefficients as a guide to water management (FAO, 2012b).

Another example of a useful tool was developed by the University of California (2013) *Nitrate Groundwater Pollution Hazard Index* to predict the susceptibility of an irrigated field to nitrate leaching. The index integrates site-specific soil, crop, and irrigation information to predict the relative susceptibility to nitrate loss. Based on the calculated results, various management options are suggested to reduce the potential for nitrate loss through leaching. Another practical model for simultaneously managing water and nitrogen is provided with the University of California (2014) tool, *CropManage*.

Advances in monitoring soil moisture will undoubtedly improve management of water and nutrients. For example, Zotarelli and Dukes *et al.* (2009) reported that the use of soil moisture sensors reduced the volume of irrigation water applied through a drip system by up to 50% compared with the regularly scheduled irrigation practices. They reported that the use of sensor-based irrigation can make significant improvements in crop water use, while reducing deep percolation and nitrate leaching.

Site-specific fertigation

Opportunities exist for improving irrigation systems to allow site-specific application of water and nutrients across a field. This improvement would result in microzones that could be independently controlled to allow spatially appropriate application of water, meeting any specific crop or soil condition (Evans *et al.*, 2013). This area of research is still being developed as irrigation technology advances.

Delivering a site-specific volume of water through an irrigation system is relatively simple by opening and closing valves. This practice can be done electronically, or field workers can make manual changes. Controlled delivery of nutrients with water is a larger challenge since it involves injecting fertilizer during the irrigation event (Coates *et al.*, 2012). Separate systems for water and nutrient delivery may be required to achieve independent control of each input. The complexity and expense of installing multiple valves and switches are still a barrier to adoption.

Summary

It is clear that large-scale improvements in the use of water and plant nutrients can be made for crop production with more careful management. Any improvements in water use efficiency for irrigated agriculture must be simultaneously coupled with advances in nutrient management. There are many examples of how these improvements can be implemented in irrigated crop production, but they all require a greater level of education and significant improvements in crop management skills. The outreach by local and regional experts on water and nutrient management can speed the adoption of these important concepts to achieve these pressing goals.

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Chapter 9

Nutrient and fertilizer management in rice systems with varying supply of water

Roland J. Buresh[1]

Abstract

Global production of rice (*Oryza sativa* L.) relies heavily on the use of well-adapted high-yielding rice varieties, fertilizer, and irrigation. Approximately 90% of the global rice production area undergoes periodic or prolonged submergence of soil with water originating from rain and irrigation. Soil submergence and corresponding restriction of soil aeration create a favorable environment for sustained production of continuous rice. Soil submergence helps control weeds, alters soil biological and chemical processes leading to increased supply of plant-available soil nitrogen (N) and phosphorus (P), and maintains soil organic matter. Competing non-agricultural demands for irrigation water will reduce its supply for rice production in the future. A corresponding reduction or elimination of soil submergence and saturation during rice production would increase penetration of air into soil (i.e. soil aeration). This could decrease the supply of plant-available N and P from soil leading to a need for additional N and P fertilizer to achieve a target yield. Less soil submergence can also increase zinc availability on acid soils and reduce zinc and iron availability on calcareous soils. Irrigation water contains potassium (K), and reduced input of irrigation water can consequently increase the need for K fertilizer to meet crop requirements for K. Regardless of the extent of soil submergence, N fertilizer should be managed to ensure adequate supply of plant-available N to match crop demand at critical growth stages of tiller development and panicle initiation. When changes in water supply alter anticipated crop yield, fertilizer use should be adjusted to match crop needs for added nutrients at a revised target yield.

[1]International Rice Research Institute (IRRI), Los Baños, Philippines, r.buresh@irri.org

Rice and water use

Rice is eaten by nearly half the world's population, making it the most popular staple food on earth. Rice grows in diverse climatic and hydrological environments, and it is harvested annually on about 160 million hectares (Mha) across an estimated 117 countries (GRiSP, 2013). About 90% of global rice production is in Asia.

Approximately 90% of the global area for rice production has earthen bunds surrounding fields to retain rain and irrigation water leading to periodic or prolonged submergence of soil with floodwater, typically of about 3 to 10 cm depth. This production of rice with deliberate retention of floodwater includes ecosystems dependent on water from only rain (i.e. rainfed lowland rice) and from a combination of rain and irrigation (i.e. irrigated lowland rice). 'Lowland rice', which is sometimes called 'wetland rice', refers to the system of producing rice on submerged soils rather than to the elevation or position in the landscape. Soils in irrigated and rainfed lowland rice production systems with prolonged submergence have historically been referred to as 'paddy soils'.

Rice is well-adapted to tropical wet seasons when intense rainfall and prolonged periods of rainfall can saturate and submerge the soil, resulting in depletion of soil oxygen (O_2) to levels insufficient for growth and survival of other major food crops. Rice tolerates soil submergence by transmitting O_2, which enters the plant from the atmosphere above the floodwater, to the stems and roots through a conduit of interconnected air-filled cavities called aerenchyma. This conduit is not present in any other major food crop except taro (*Colocasia esculenta* (L.) Schott).

Ample water for submergence of soil with floodwater enabled the sustainable cultivation of rice for millennia at low, but relatively stable yields. Sufficient irrigation water for soil submergence together with the use of fertilizer and modern high-yielding varieties were vital ingredients contributing to the Green Revolution in rice production.

Irrigated rice occupies nearly 58% of the global rice area and provides about 75% of global rice supply (GRiSP, 2013). One rice crop per year is grown in temperate environments and high-altitude areas in the tropics. Continuous rice cropping with two, and occasionally three, rice crops per year is common for irrigated environments in tropical Asia. In such cases, irrigation supplements rain in the wet season, but the rice crop is highly reliant on irrigation in the dry season. Long-term experiments indicate that continuous cultivation of two and three rice crops per year can be sustained through the combination of sufficient irrigation to maintain soil submergence, balanced fertilizer inputs, and the use of recently released rice varieties with resistance to pests and diseases (Dobermann *et al.,* 2000; Pampolino *et al.,* 2008). Rice in rotation with other crops, particularly wheat (*Triticum aestivum* L.) is common in the subtropics of South Asia and China. The rice–maize (*Zea mays* L.) cropping system is gaining importance on paddy soils across tropical and subtropical Asia in response to the increasing demand of maize for animal feed.

Rainfed lowland rice with earthen bunds to retain water occupies near 33% of the global rice area and provides about 19% of global rice supply (GRiSP, 2013). Rainfed lowland rice environments can experience high uncertainty in timing, duration, and intensity of rainfall, which correspondingly results in uncertainty and variations

in the duration and depth of soil submergence. Rainfed lowlands can be affected by both drought and uncontrolled flooding, ranging from flash floods to prolonged submergence of soil under a layer of water, which can exceed the height of the rice crop. Additional constraints arise from the widespread incidence of soils with poor physical and chemical properties, including soil salinity and acidity.

Rice production without bunds for deliberate retention of water is largely confined to rainfed areas, ranging in topography from flat to steeply sloping. This production system is referred to as 'rainfed upland rice' and occupies nearly 10% of the global rice production area, but it contributes only 4% of global rice production because yields are low (GRiSP, 2013). The soil is not inundated or saturated except for brief periods after intense or prolonged rain.

Rice is a major beneficiary of irrigation water resources, receiving an estimated 34-43% of global irrigation water (Bouman *et al.*, 2006). An estimated 24-30% of the world's developed freshwater resources are used for irrigation of rice. Much of the world's rice is produced in countries with rapidly growing economies. With economic growth comes competing demand for use of water by industries and households in addition to agriculture. Groundwater has become an important source for irrigation, particularly in South Asia, but groundwater tables are falling in many areas leading to increased costs for pumping water (Bouman *et al.*, 2007) and depleted water resources. Rice production in some irrigated lowlands can consequently anticipate future increases in cost and scarcity of irrigation water.

This could encourage either the production of lowland rice with less water or the diversification in the water-scarce season to non-rice crops, which could result in a shift of lowland rice production to more water-abundant areas. The production of rice with less water could reduce or eliminate soil submergence during the rice-growing season, whereas a shift toward more non-rice crops in a rice-based cropping system would extend the duration of soil aeration within the cropping system. Such reductions in soil submergence with increased soil aeration can alter biological and chemical processes within soil thereby influencing nutrient availability and fertilizer requirements.

Water use in rice production is particularly affected by land preparation and crop establishment practices, which can vary with farm size, availability of inexpensive labor, and access to mechanization. Rice cultivation practices in Asia, where rice is mostly produced on farms each smaller than one hectare, have relied on manual labor with increasing use of small-scale mechanization as labor becomes less available or more expensive. Rice cultivation on large landholdings such as in Australia, Europe, North America, and South America on the other hand relies on large-scale mechanization.

Crop establishment

Much of the rice in small landholdings in Asia is established by manual transplanting. Rice seedlings are first raised in a seedbed, and then after about 2 to 5 weeks the seedlings are planted in the main field. Manual transplanting is labor-intensive. As costs and scarcity of labor increase, mechanized transplanting can provide an alternative to manual transplanting.

A labor-saving alternative to transplanting is sowing germinated rice seed onto the surface of wet soil (i.e. wet-seeded rice). The seed can be either manually broadcast or mechanically dropped in rows from a drum seeder. Wet-seeded rice is more reliant than transplanted rice on effective land leveling and with early control of water depth to ensure a uniform crop stand. Wet seeding is favored relative to transplanting in areas with relatively high labor costs and good control of irrigation water such as in the Mekong Delta of Vietnam, the Central Plain of Thailand, Sri Lanka, and parts of the Philippines.

Another alternative is sowing seed on dry or moist soil (i.e. dry-seeded rice). The seed can be either manually broadcast onto the soil surface or drill seeded into the soil. Dry-seeded rice requires much less labor than transplanting and, historically, it has been practiced in some rainfed areas of Asia. Dry seeding is conducive to mechanization, and mechanized drill seeding into dry or moist soil is commonly practiced in large-scale rice production in the south central United States. Dry seeding is an emerging practice in relatively smaller-scale rice production in the northwestern Indo-Gangetic Plain of India (Ladha *et al.*, 2009).

Weeds can emerge soon after establishment of rice. Transplanted rice seedlings are already several weeks old before weeds emerge, enabling the seedlings to compete with weeds. Wet- and dry-seeded rice, on the other hand, can emerge at nearly the same time as weeds resulting in greater constraints from weeds and more dependence on effective use of herbicides.

Land preparation

Nearly all lowland rice fields in Asia are deliberately flooded before plowing and harrowing or rotavation (IRRI, 2014). This tillage of saturated soil, referred to as puddling, destroys soil aggregates and creates a soft, muddy, 10- to 20-cm-deep layer overlying a hardpan. The hardpan restricts downward flow of water thereby reducing loss of nutrients by leaching and helping to maintain a layer of floodwater (Sharma and De Datta, 1986). The floodwater helps reduce germination and emergence of weeds. It also helps control some rice pests such as root-knot nematode (*Meloidogyne graminicola* Golden & Birchfield).

The most common alternative to puddling is conventional tillage of dry or moist soil, such as that practiced for wheat (Figure 1). Less common alternatives are reduced tillage and no-till systems for rice establishment (Ladha *et al.*, 2009). Irrigated rice in Australia, Europe, North America, and South America is usually grown on non-puddled soil.

Puddling creates a soft topsoil layer favorable for transplanting of seedlings and for wet-seeded rice but not for dry-seeded rice (Figure 1). Most rice production on non-puddled soils is dry seeded. Aerial seeding of germinated seed into floodwater, a variant of wet-seeded rice referred to as 'water-seeded rice', is common in California. Mechanized transplanting of rice on non-puddled soil is under investigation as a possible water and labor saving alternative to traditional transplanted rice on puddled soil, which might be less susceptible to weed constraints than dry-seeded rice.

LAND PREPARATION

Figure 3 diagram content:

Puddled → Transplanted → Manual, Mechanical

Puddled → Wet seeded

Non puddled → Conventional tillage / Reduced tillage, No till

CROP ESTABLISHMENT: Transplanted, Wet seeded, Dry seeded, Water seeded, Mechanical transplanted
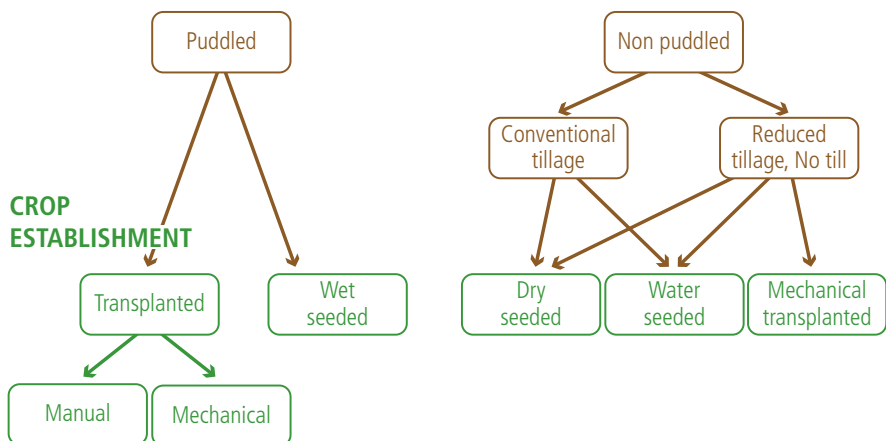
IRRIGATION REGIME: Flooded, Safe soil drying, Unsafe soil drying, Flooded, Safe soil drying, Unsafe soil drying, Safe AWD, Aerobic rice

Figure 3. Combinations of land preparation, crop establishment method, and water regime likely to be encountered with irrigated rice. Each water regime could occur with each crop establishment method.

Water flows in a rice field

A rice paddy requires water for puddling soil and then for matching the outflows by evaporation, transpiration, percolation, seepage, and surface runoff over the bund (Box 1) (Bouman *et al.,* 2006, 2007). Estimates of water use for puddling range from about 100 to 940 mm (depth of water per surface area) per cropping season and depend on the degree of water control and the time interval from initial land soaking to crop establishment. After crop establishment the soil in irrigated lowlands is typically kept submerged to a depth of about 3 to 10 cm. In rainfed lowlands the depth and duration of flooding can vary greatly depending on rainfall. Some irrigated rice in the south central United States is dry seeded on non-puddled soil with delayed irrigation for soil submergence. Soil submergence in this 'dry-seeded, delayed flood' practice of rice production starts at the beginning of tillering and continues until just before harvest.

The irrigation water needed for one cropping season, including land preparation, in a lowland rice field depends on soil properties, depth to the groundwater table, rainfall, and net losses of water by evaporation, transpiration, percolation, seepage, and

Box 1. Inflows and outflows of water in a lowland rice field.

The outflows (losses) of water in a lowland rice field include transpiration, evaporation, percolation, seepage, and surface runoff over the bund surrounding the field. Transpiration is the water released as vapor by the plants, and evaporation is the water lost as vapor from the surface of the water layer or soil. Seepage is the lateral subsurface flow of water beneath or through bunds, and percolation is the vertical flow of water to the zone below the roots. Overbund flow or surface runoff is the spillover when water depth rises above the height of the bund.

Combined evaporation and transpiration (evapotranspiration) rates for rice fields are typically about 4-5 mm per day in the wet season and 6-7 mm per day in the dry season (Bouman *et al.*, 2006, 2007). They can reach 10-11 mm per day in subtropical regions immediately before the onset of the monsoon. Combined seepage and percolation rates typically vary from 1 to 5 mm per day for heavy clay soils, and from 25 to 30 mm per day for sandy and sandy loam soils. Water losses by seepage and percolation can account for 25-85% of all water inputs (Bouman *et al.*, 2006).

The inflows of water into a lowland rice field include rainfall and irrigation as well as overbund inflow and seepage from higher fields. Capillary rise is the upward movement of water from the groundwater table. It is negligible in a submerged soil because percolation prevents the upward movement of water into the root zone.

INFLOWS
R - Rainfall
I - Irrigation
S_{IN} - Seepage from higher field
O_{IN} - Overbund inflow
C - Capillary rise

OUTFLOWS
E - Evaporation
T - Transpiration
S_{OUT} - Seepage into lower field
O_{OUT} - Overbund outflow
P - Percolation

Bund
Floodwater
Puddled soil
Plow layer
Subsoil
Groundwater
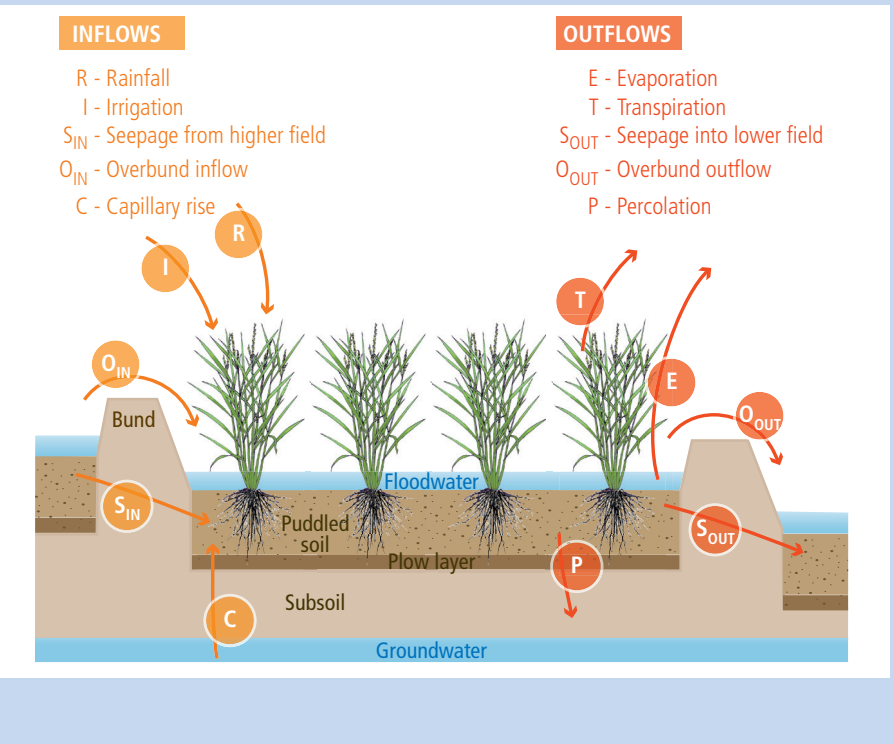
overbund flow (Box 1). Total water inputs from rainfall plus irrigation can be as low as 400 mm on heavy clay soils with a shallow water table directly supplying water for crop transpiration. Water inputs from rainfall plus irrigation, on the other hand, can exceed 3,500 mm on soils with deep groundwater tables not supplying water for crop transpiration (Saharawat *et al.,* 2010). A cited 'average' value for input from rainfall plus irrigation during an entire cropping season is 1,300-1,500 mm (Bouman *et al.,* 2007). This corresponds to 13-15 megaliters (ML) ha^{-1}.

Evaporation and transpiration are vital for crop production and represent outflows of water that cannot be reused. Seepage, percolation, and overbund flow represent losses of water from a field that can be often captured and reused in downstream fields (Molden *et al.,* 2007). They consequently represent reusable flows of water (Box 1) rather than water depletion at the scale of the irrigation area or basin, but the extent of water reuse is generally not known. Water salinity typically increases with reuse and this could limit reuse of water within an irrigation area or basin.

Water productivity, expressed in terms of produced grain mass per cumulative mass of water outflow by evaporation plus transpiration (evapotranspiration), is comparable for rice and wheat, which are both C_3 cereals (Bouman *et al.,* 2006, 2007). The seasonal water input from rainfall plus irrigation is however usually higher for lowland rice than for wheat because of high water outflows by seepage, percolation, and overbund flow in rice production with soil submergence. Water productivity expressed in terms of produced grain mass per cumulative mass of total water input from rainfall plus irrigation would consequently be lower for rice than for wheat.

Rice is relatively sensitive to salinity, especially during early seedling growth and the reproductive phase, but researchers have found considerable variation in rice germplasm for tolerance to salinity. This provides encouragement for developing high-yielding rice varieties with greater tolerance to salinity, which could enable irrigation with water exceeding current thresholds for salinity (GRiSP, 2013).

Soil processes

Air, which contains 21% O_2, readily moves into and through soils not saturated with water. This rapid transport of air ensures a sufficient supply of O_2 to plant roots and soil microorganisms. The submergence of soil results in saturation of soil pores with water and a layer of floodwater on the soil. They markedly restrict movement of O_2 into and through soil because O_2 moves 10,000 times slower through water than through air.

When soil is submerged, the existing O_2 in the soil is rapidly consumed through cellular respiration of soil organisms, and the floodwater restricts movement of additional O_2 into the soil. When soil O_2 disappears, aerobic soil microorganisms, which require O_2, rapidly die and are replaced by anaerobic microorganisms (i.e., anaerobes) capable of anaerobic respiration in the absence of O_2.

The O_2 in air passing through the floodwater to the soil is rapidly consumed within the water layer and at the soil surface (Figure 2). The O_2 only penetrates up to several mm into the soil, resulting in a thin aerated soil layer (i.e. 'aerobic layer' or 'oxidized
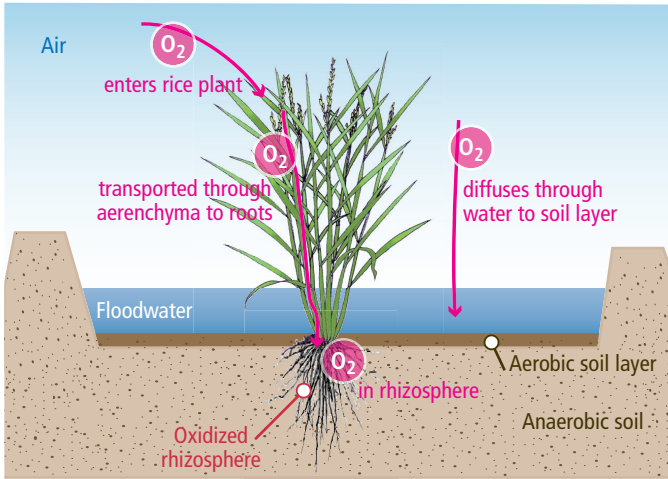
Figure 2. The entry of air with oxygen (O_2) into submerged soil and the formation of a thin aerobic surface soil layer and an oxidized rhizosphere (root-soil interface) adjacent to the bulk anaerobic soil.

layer'). Beneath this layer is the bulk soil depleted of O_2 and populated by anaerobic microorganisms (i.e. 'anaerobic soil').

Air with O_2 enters the rice plant from above the floodwater and is transported through aerenchyma, a conduit of air-filled cavities, to the stem and roots (Figure 2). Some of this O_2 leaks through root pores into the surrounding soil resulting in a thin rhizosphere of oxidized soil around individual roots (root-soil interface) adjacent to the bulk anaerobic soil. The rhizosphere supports aerobic microorganisms that prevent potentially toxic soil components from entering the rice root.

Anaerobic microorganisms, in the absence of O_2 use oxidized soil components in their respiration. This results in a cascading change in soil components following the sequence of nitrate (NO_3^-), manganese (Mn^{4+}), iron (Fe^{3+}), and sulfate (SO_4^{2-}), eventually leading to the formation of methane (CH_4) (Figure 3) (Ponnamperuma, 1972; IRRI, 2009). Nitrate becomes unstable soon after soil submergence leading to its rapid loss as nitrogen gas (N_2) through the process of denitrification. This highlights why nitrate-based fertilizers are not recommended for submerged soils.

The change in the form of iron (Figure 3) results in conversion of relatively insoluble iron phosphate compounds to more soluble compounds, thereby contributing to increased plant availability of phosphorus (P) in submerged soils. The reduction of sulfate produces sulfide capable of binding zinc and reducing plant-available zinc in submerged acid soils. The cascading sequence eventually leads to the formation of methane, rather than carbon dioxide, as the gaseous end product from the decomposition of organic materials (Wassmann *et al.,* 2000). High levels of Fe^{3+} and sulfate can delay the cascading sequence of changes (Figure 3) thereby delaying and retarding methane formation.
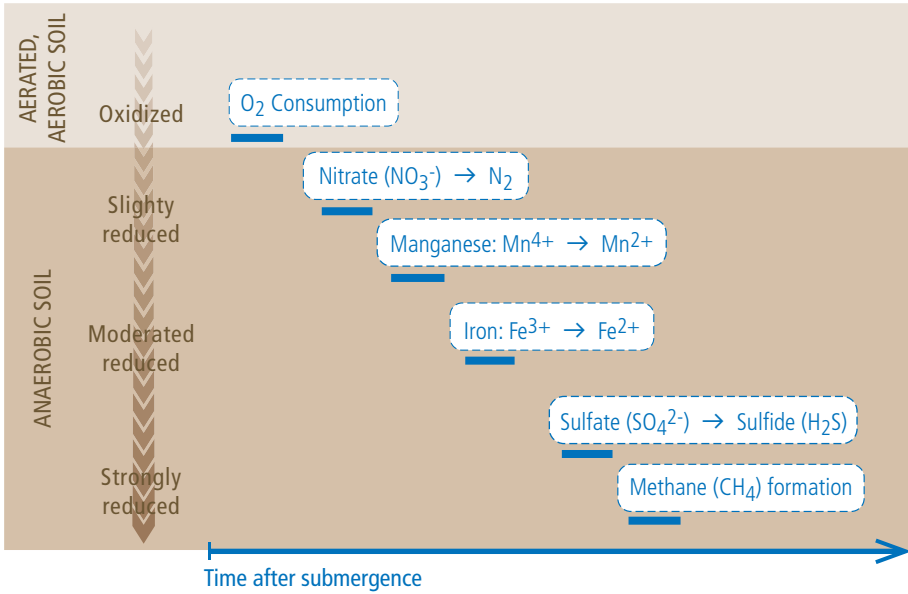
Figure 3. Cascading change in soil components after the rapid initial depletion (consumption) of oxygen (O_2) during soil submergence.

Nutrient management

Based on 2010 statistics, global rice production accounts for 15% of global fertilizer nitrogen (N) use and 13% of global fertilizer P and potassium (K) use (Heffer, 2013). In Asian rice production, fertilizer is often the second most important input cost, after labor, accounting for 15-30% of total production costs for irrigated rice in Asia depending on government subsidies and labor costs (Moya *et al.,* 2004; Pampolino *et al.,* 2007).

Rice is grown on six continents on an estimated 144 million farms, mostly smaller than one hectare each and located in Asia (GRiSP, 2013). These small rice farms, and fields within farms, can vary in fertilizer use, yield, crop management, crop response to applied nutrient, and nutrient balances, which directly affect their fertilizer needs. Traditional blanket fertilizer recommendations for large areas or agroecological zones fail to account for these spatial and temporal variations in field-specific needs for nutrients. Site-specific nutrient management (SSNM) for rice originated from the mid-1990s as an alternative approach for dynamically supplying fertilizer to match field-specific needs of rice for supplemental N, P, and K (Dobermann *et al.,* 2002).

Nitrogen

Nitrogen is the nutrient most limiting rice production. Field-specific management of N fertilizer based on the SSNM approach involves an initial estimate of the total

requirement for fertilizer N and then the distribution of this N during the cropping season to match crop needs. The requirement for fertilizer N for a given field and season is determined by first setting a target yield attainable with the anticipated crop management, water regime and climate conditions. For rice farmers not optimally supplying N fertilizer during the season, the target yield can be set moderately higher than the farmer's current yield in anticipation of higher yields with improved timing of fertilizer N. The upper limit for the target yield depends on climate and variety. After setting the target yield, the fertilizer N required to attain the target can be calculated from the anticipated gain in yield from applied N and an attainable efficiency of fertilizer N use (Box 2).

Box 2. How to determine the N fertilizer requirement for rice.

The fertilizer N (FN, expressed in kg ha^{-1}) required to attain the target grain yield (GY, expressed in kg ha^{-1}, can be calculated from the anticipated gain in yield from applied N and an attainable agronomic efficiency of fertilizer N (AE$_N$, expressed in kg grain yield increase per kg N applied):

$$FN = (GY - GY_{0N})/AE_N \qquad [1]$$

where, GY$_{0N}$ is the N-limited yield expressed in kg ha^{-1}, and (GY − GY$_{0N}$) is yield gain from applied N. The N-limited yield serves as an approximation of the supply of N from all sources other than fertilizer. For a given yield target, it can be estimated using small plots without added N fertilizer distributed across contrasting rice fields (Dobermann *et al.*, 2003). Target AE$_N$ can be obtained from published research.

Regardless of rice-growing environment and water regime, N fertilizer should be managed to ensure a sufficient supply of N to meet crop needs at the critical growth stages of tiller development and panicle initiation. An insufficient supply of N at tiller development could restrict the number of tillers and potentially result in an inadequate number of panicles to achieve the target yield. An insufficient supply of N to meet crop demand at panicle initiation can adversely affect yield through a reduced number of filled spikelets per panicle. In Asian rice production, the supply of labor is typically sufficient to manually broadcast N fertilizer, typically as urea, at tiller development and panicle initiation. In rainfed lowland rice environments the timing and management of fertilizer N can require adjustments when drought or flooding coincides with the scheduled time for fertilizer application.

Nitrogen fertilizer broadcast into lowland rice fields is susceptible to gaseous losses, especially by ammonia volatilization (Buresh *et al.,* 2008). The N fertilizer broadcast before tillering is most prone to loss because of the low demand of the rice crop for N. Nitrogen applied at tillering and panicle initiation is taken up faster by rice and is less susceptible to losses. The efficiency of N fertilizer use can be increased by avoiding excess early supply of N before tillering and ensuring N is supplied at rates matching the crop's need for supplemental N.

Phosphorus and potassium

Regardless of the rice-growing environment and water regime, the field-specific management of P and K based on SSNM principles involves an estimate of fertilizer P and K requirements using a combination of nutrient balances and expected yield gains from applied P and K (Witt and Dobermann, 2004; Buresh *et al.,* 2010) (Box 3). Based on experiences with irrigated rice in Asia, fertilizer P requirements calculated by yield gain (equation 4, in Box 3) are typically lower or comparable to fertilizer P requirements calculated by nutrient balance with P input equal P output (equation 2, in Box 3) when P inputs from organic materials are minimal.

Fertilizer K requirements calculated from field-level K balances (equation 3, in Box 3) depend greatly on inputs of K from irrigation water, management of crop residues, and input of organic materials. In irrigated rice fields the input of K with irrigation could approximate the removal of K with harvested grain when all crop residues are retained. Mechanical harvesting with a combine harvester removes the grain and leaves all crop residue in the field. In such a case, the field-level K balances would indicate little or no need for fertilizer K.

On the other hand, when much or all of the crop residues are removed from the field, (e.g. by manual harvesting and off-site threshing), the fertilizer K requirements determined by K balance (equation 3, in Box 3) can be markedly higher than fertilizer K requirements determined by yield gain (equation 5, in Box 3). Fertilizer K requirements can be estimated by combining the yield gain and nutrient balance approaches to appropriately address the trade-off between higher net income achieved with moderate K rates to overcome K deficiency but allow mining of soil K (K input < K output) versus lower net income achieved with higher K rates to minimize mining of soil K.

All P fertilizer is normally recommended immediately before or soon after crop establishment to ensure ample P for early root development. All or most of the required K is typically recommended for application immediately before or soon after crop establishment. In fields with high requirement for fertilizer K, where yields are high and there was partial or complete removal of crop residues from the previous crop, up to half of the total K fertilizer can be applied with N fertilizer at panicle initiation. This application of K can improve grain filling.

The SSNM approach provides algorithms used in decision-making tools for determining field-specific fertilizer requirements (Box 4). This tool uses SSNM-based algorithms together with information from a rice farmer and other sources to calculate a field-specific fertilizer recommendation. The recommendation can be adjusted for anticipated effects of irrigation water management on yields and optimal timing of N.

Organic materials

Some Asian countries have promoted organic materials as nutrient sources for rice production in response to rising costs of industrial fertilizers. Organic materials must undergo biological decomposition, which releases nutrients in inorganic forms that can be taken up by rice. The supply of nutrients from decomposing organic materials does not typically match the demand of rice for all yield-limiting nutrients. The supply of plant-available nutrients from added organic materials can fail to meet crop requirements for some nutrients while exceeding crop requirements for other nutrients.

Box 3. How to determine the P and K fertilizer requirements for rice.

Fertilizer P (FP, expressed in kg ha^{-1}) and fertilizer K (FK, expressed in kg ha^{-1}) required to attain the target grain yield (GY, expressed in Mg ha^{-1}) can be calculated using either a nutrient balance or yield gain approach. With the nutrient balance approach FP and FK are calculated based on estimated outputs and inputs of the nutrient of interest within a field or area of production:

$$FP = (GY \times RIE_P) - P_{CR} - P_{OM} - P_S \qquad [2]$$

$$FK = (GY \times RIE_K) - K_{CR} - K_W - K_{OM} - K_S + K_L \qquad [3]$$

where, P_{CR} and K_{CR} are P and K inputs with retained crop residues, K_W is the K input with irrigation water for an entire cropping cycle, P_{OM} and K_{OM} are P and K inputs from added organic materials, and K_L is downward loss of K from the root zone. All inputs and outputs are expressed in kg nutrient per ha.

The RIE_P and REI_K reflect the typical amount of the respective nutrient in a mature rice plant. They are referred to as reciprocal internal efficiencies (Buresh *et al.*, 2010) and expressed as kg nutrient accumulated in above-ground crop dry matter at maturity per Mg of grain production. Based on an analysis of large datasets RIE has been estimated as 2.7 kg P and 15.9 kg K per Mg grain yield for rice with harvest index ≥0.4 (Buresh *et al.*, 2010). The inclusion of P_S in equation 2 and K_S in equation 3 enables a drawdown of P and K from soil reserves up to a threshold expressed in kg per ha, which can be adjusted for soil properties. When P_S or K_S=0, the calculated fertilizer requirement for a nutrient ensures input = output with no drawdown of nutrient from soil reserves (Buresh *et al.*, 2010).

With the yield gain approach, FP and FK are calculated from the anticipated gain in grain yield from the applied nutrient:

$$FP = (GY - GY_{OP}) * RIE_P/RE_P \qquad [4]$$

$$FK = (GY - GY_{OK}) * RIE_K/RE_K \qquad [5]$$

where, GY_{OP} is the P-limited yield expressed in Mg per ha, and GY_{OK} is the K-limited yield expressed in Mg per ha. The P- and K-limited yields serve as approximations of the supply of the nutrient of interest from all sources other than fertilizer, which can be estimated from nutrient omission plots distributed across contrasting rice fields (Dobermann *et al.*, 2003). The RE_P and RE_K are recovery efficiencies for fertilizer P and fertilizer K, respectively, for mature rice. Recovery efficiencies can vary across fields. In an on-farm evaluation of SSNM for irrigated rice across Asia, RE_P averaged 0.25 kg plant uptake of fertilizer P per kg applied P and RE_K average 0.44 kg plant uptake of fertilizer K per kg applied K (Witt and Dobermann, 2004).

Box 4. A decision-making tool for fertilizer management in rice production

The determination of field-specific fertilizer requirements and management, using an SSNM approach as outlined in Boxes 2 and 3, has been incorporated into decision-making tools. One such tool is *Rice Crop Manager*, which is an upgrade from the earlier *Nutrient Manager for Rice*. Country- or region-specific versions of this Web-based tool are available and under development (http://cropmanager.irri.org).

Rice Crop Manager is targeted for use by extension workers, crop advisers, service providers, and input providers to interview a farmer or farmer group using a computer or smartphone. The information obtained on the farmer's farming practices is used to automatically generate a crop and nutrient management recommendation customized to the rice farming conditions and needs of the farmer. The recommendation can be provided to farmers as a printout or through a short message service (SMS).

Rice Crop Manager determines field-level N fertilizer requirement using equation 1 in Box 2. The field-level P fertilizer requirement is determined by the nutrient balance approach given in equation 2 in Box 3, except the input of P from organic materials is adjusted to account for delay in supply of plant-available P until after organic materials decompose. The K fertilizer requirement is determined using a combination of equations 4 and 5 in Box 3.

1 **Obtain information from farmer**
- Smartphone
- Personal computer

2 **Calculate management practices**

Crop manager model
- SSNM-based nutrient management calculator
- Calculator for crop management decision making

CLOUD BASED SERVER
Databases and spatial information
- Variety traits
- Variety- and management- adjusted target yields
- Soil characteristics

3 **Provide actionable recommendation**
- Printed guidelines
- SMS

Added organic materials do not often supply sufficient plant-available N to eliminate N deficiency in rice. In such a case, the integrated use of industrial N fertilizer with organic materials is required to supply sufficient plant-available nutrient to meet the needs of a high-yielding rice crop. The merit of organic materials as a nutrient source should be based on the comparative cost for use of organic materials versus use of industrial fertilizers to achieve a targeted rice yield (Buresh and Dobermann, 2010).

The incorporation of organic materials, including crop residues, to submerged soil can have some detrimental effects. Organic materials, including crop residues, can hasten the changes in soil components shown in Figure 3. This can accelerate conversion of sulfate to sulfide that can precipitate zinc and thereby reduce its availability to the rice crop, enhance production and emission of methane, and favor formation of organic acids that can adversely affect rice growth. Soil drying and aeration can reduce these effects.

Responses to water scarcity

Rice production on puddled soil

The use of irrigation water on puddled soils can be reduced by lowering the depth of floodwater and by allowing the soil surface to dry before the next application of irrigation water (Bouman *et al.,* 2007; IRRI, 2014). The practice of withholding irrigation until several days after the disappearance of floodwater has been referred to as 'controlled irrigation', 'intermittent irrigation', and 'alternate wetting and drying' (AWD). Even without floodwater, rice roots can access water in the saturated subsurface soil.

The practice of 'safe' AWD now promoted for reduced use of irrigation water entails withholding irrigation in the rice-growing season until the water level falls to a threshold depth about 15 cm below the soil surface (Price *et al.,* 2013; IRRI, 2014). Implementing AWD requires good control of irrigation water to ensure timely delivery of water to the field. It also requires maintaining standing floodwater at the critical water-sensitive stage of flowering, from one week before to one week after the peak of flowering. Safe AWD, as compared to irrigation with continuous soil submergence, can reduce use of irrigation water, reduce accumulation of arsenic (Norton *et al.,* 2012) and cadmium (Yang *et al.,* 2009) in grain, increase zinc availability in acid soil, and reduce methane emissions (Bouman *et al.,* 2007). It can however require more labor for weed control, and the absence of floodwater increases risk of crop damage from rats.

'Safe' AWD often reduces input of irrigation water by about 15% with no loss in yield. The actual performance of AWD varies depending in part on depth to groundwater. On soils with a consistent shallow depth to groundwater of <40 cm, AWD can save moderate amounts of irrigation water (10-15%) without a yield loss. On soils with groundwater below the depth accessible by rice roots, AWD can save larger amounts of irrigation water, but this can result in the trade-off of reduced yield (Bouman *et al.,* 2007).

Reduced use of irrigation water with AWD would result in a corresponding reduction in outflow of water (Box 1). A reduction in evaporation represents a 'real' reduction in

water use, which would have been otherwise unusable by rice. Outflows of water by seepage, percolation, and overbund flow can be captured and reused downstream and therefore do not represent water depletion at the scale of the irrigation area or basin. A reduction in irrigation water use with AWD in an isolated field could overestimate actual water saving for AWD in an irrigation area or basin because isolated fields with AWD can benefit from inflows of water from upper fields not practicing AWD.

Farmers are often attracted to AWD by the reduced costs for pumping irrigation water or by the reduced costs for water with volumetric pricing. Farmers paying a fixed rate for irrigation based on land area rather than quantity of water would not immediately benefit from using less irrigation water by AWD (Price *et al.,* 2013), although there might be long-term or broader-scale benefit via reduced use of the water resource in general.

The System of Rice Intensification (SRI) originated from Madagascar as an agroecological method for growing rice with fixed guidelines including the use of young seedlings, transplanting with a single seedling, wide plant spacing, controlled irrigation, manual and mechanical weeding, and application of organic materials without the use of industrial fertilizers (Dobermann, 2004; Tsujimoto *et al.,* 2009; Bouman, 2012). The term 'SRI' has, in recent years, come to be associated with sets of good agronomic management practices typically differing from the SRI originating from Madagascar. 'SRI' can now refer to rice management practices that differ among countries and rice-growing areas. In most cases, a component of 'intermittent irrigation' or AWD is included, but farmers can find it difficult to practice AWD when irrigation and drainage infrastructure are poorly developed (Ly *et al.,* 2012). Because AWD is only one component of SRI, the benefits of AWD per se cannot be readily separated from other components of SRI.

Rice production without soil puddling

The initial soaking of rice fields before puddling and then the subsequent puddling process, as commonly practiced in Asia, can consume considerable amounts of water (Tuong and Bouman, 2003) that depend on the cracks in the dry soil immediately before soaking, the degree of water control, and the time interval from initial land-soaking to crop establishment. Water is also required for raising seedlings when rice is transplanted. An approximate water input from rainfall and irrigation for land-soaking and land preparation is 200-300 mm (Sudhir-Yadav *et al.,* 2011b).

Tabbal *et al.* (2002) reported an exceptionally high water use of 940 mm for soaking and land preparation before transplanting rice in an irrigation system in the Philippines. This high water use can be attributed to the continuous flooding of the entire rice production area from the start of seedbed preparation, resulting in nearly 2 months from the first irrigation to completion of transplanting in the production area.

The elimination of soil puddling is typically associated with a conversion from either transplanted or wet-seeded rice to dry-seeded rice with less-intensive tillage than puddling, thereby reducing fuel costs (Figure 1). The elimination of puddling increases the susceptibility of dry-seeded rice to downward movement and loss of water during the cropping period and to yield loss from weeds.

Rice production on non-puddled soil without permanent submergence

Rice grown on non-puddled soil is typically dry seeded. It can vary greatly in water regime from continuous soil submergence, to alternate soil wetting and drying, to unsaturated soil. Water can be saved by reducing irrigation and soil submergence during the rice crop, but there can be a trade-off of reduced yield with reduced use of irrigation water depending on the severity of water deficit (Sudhir-Yadav *et al.,* 2011a, 2012).

Irrigation water can be reduced without a yield loss as compared to continuous soil submergence through frequent irrigation to maintain soil water content in the root zone between saturation and field capacity. The 'safe' threshold for allowable soil drying without yield loss can vary with soil, number of drying cycles, and timing of water stress (Sudhir-Yadav *et al.,* 2012). This 'safe soil drying' (Figure 1) requires good irrigation control and effective control of weeds. This production system is being introduced for reduced use of irrigation water in the northwestern Indo-Gangetic Plain of India.

More water can be saved by growing rice like wheat or maize on non-puddled soil without deliberate flooding, but water deficits can result in yield loss. With this practice the soil remains aerated throughout the rice-growing cycle and soil water content in the root zone can drop below field capacity, except following heavy rainfall. Irrigation water is applied when rainfall is insufficient to maintain soil water content above a threshold set between field capacity and wilting point. This is called 'aerobic rice' (Bouman *et al.,* 2007; IRRI, 2014) and is usually established by dry seeding. Drying of soil below field capacity results in 'unsafe soil drying' (Figure 1) and can result in a yield penalty depending on the water deficit. Weeds and root-knot nematodes are potential constraints on aerated soils (Kreye *et al.,* 2009), and iron deficiency can be a constraint on aerated soil with high pH in the northwestern Indo-Gangetic Plain of India (Sudhir-Yadav *et al.,* 2012).

Crop diversification

When irrigation water is limited, farmers can choose to grow a crop other than rice such as maize, potato (*Solanum tuberosum* L.), or vegetables, which can be selected based on market prices. The non-rice crop would be typically grown on well-drained soils with water content between field capacity and wilting point, which is comparable to the range for growth of aerobic rice.

Implications of water use on soil processes

Soil submergence favors sustained rice production by controlling weeds and some soil-borne pests, and by conserving soil organic matter (SOM), which serves as a source of nutrients. Some SOM and capacity of soil to supply nutrients can be lost when rice monoculture on puddled and submerged soil is converted to production of rice with less water or to rotation of rice with other crops. Resource-conserving technologies to grow rice using reduced or zero tillage with establishment by drill seeding or mechanical transplanting aim to prevent further loss of SOM and potentially slowly build up SOM (Ladha *et al.,* 2009).

Soil submergence contributes to a sustained input of plant-available N through biological fixation of atmospheric N_2 (BNF) by organisms residing in saturated soil and floodwater (Buresh *et al.,* 2008). This supply of indigenous N for rice enables the sustained production of rice at low yields in plots without added N fertilizer and organic materials. Soil submergence also enhances the availability of soil P through increased mobility of phosphate ions and conversion of insoluble phosphate compounds to more soluble forms.

Ammonium is the stable form of inorganic N in submerged soils, whereas nitrate accumulates in aerobic soils. Nitrate can accumulate in lowland rice production systems during the growth of a non-rice crop, growth of rice on unsaturated soil, and a fallow period before rice cultivation (Buresh *et al.,* 1989). This accumulated nitrate is prone to rapid gaseous loss by denitrification when soil is submerged during rice growth or during land preparation for a subsequent rice crop (Buresh *et al.,* 2008). Nitrate loss by leaching is typically small in lowland rice production, even on unpuddled soil (Liang *et al.,* 2014). Leaching rather than denitrification can occur on sandy soils with high downward water flow and little supply of the organic matter substrate required by soil microorganism capable of denitrification.

Soil submergence promotes the production of methane by anaerobic decomposition of SOM and added organic materials, whereas aeration of soil reduces methane emissions. Nitrous oxide, another greenhouse gas with a higher global warming potential (GWP) than methane, is produced during denitrification. Emissions of nitrous oxide are typically negligible or low during continuous soil submergence; but soil drying and subsequent flooding, which result in the formation and loss of nitrate, favor the emission of nitrous oxide.

Management practices that respond to water scarcity such as AWD, aerobic rice, and the inclusion of more non-rice crops in the cropping system can reduce emissions of methane while increasing the emissions of nitrous oxide. The integrated GWP for the two gases must be considered when assessing a water management practice. A pot study suggested that AWD has a comparable or lower GWP than continuous soil submergence when crop residues are incorporated but not when crop residues are removed (Johnson-Beebout *et al.,* 2009).

Implications of water use on nutrient management

As a general principle, a marked reduction in submergence could tend to increase fertilizer N, P, and K requirements for a given target yield. A higher need for fertilizer N can arise from lower BNF and possible lower net N mineralization in aerobic soil than in submerged soil. A higher need for fertilizer P can arise from the reduced availability of soil P in aerobic soil (Dobermann and Fairhurst, 2000). The need for K fertilizer is influenced by management of crop residues and K inputs from irrigation water.

Soil aeration increases zinc availability on acid soils (Dobermann and Fairhurst, 2000), but it can decrease zinc and iron availability on high-pH soils, leading to a need for iron and zinc fertilization for dry-seeded aerobic rice (Malik and Yadav, 2008).

Fertilizer rates should be adjusted to the anticipated water-limited grain yield of rice (Haefele and Bouman, 2008).

The use of safe AWD on puddled soil without loss of rice yield results in periodic soil aeration, but the extent and duration of soil drying are relatively mild; and current research does not indicate a significant change in SOM and plant availability of macronutrients for safe AWD as compared to continuous soil submergence. The need of rice for fertilizer N, P, and K at a given yield level is consequently unchanged. Nutrient best management practices are the same for rice grown with AWD and continuous soil submergence, provided AWD does not result in water stress leading to lower yield (Cabangon *et al.,* 2011).

Alternating soil drying and wetting in AWD might favor gaseous loss of broadcast fertilizer N and soil N by sequential nitrification-denitrification (Buresh *et al.,* 2008). The risk of N loss could be reduced by avoiding excess supply of fertilizer N before tillering. Such N loss would decrease with increasing age of rice due to increased competition of rice with microorganisms for ammonium before conversion to nitrate (i.e. nitrification) and for nitrate before denitrification (Buresh *et al.,* 1993).

Broadcasting urea immediately before irrigation could help ensure the movement of N into the soil, where it would be less prone to loss via ammonia volatilization (Buresh *et al.,* 2008). In areas where irrigation water flows across fields or irrigation water is prone to loss by overbund outflow, the urea can be broadcast after irrigation to reduce risk of N loss with outflow of irrigation water.

Conclusions

Much rice will continue to be produced in monsoonal Asia in the wet season when intense rains submerge soils and create an environment for which rice is better adapted than other major food crops. This seasonal submergence of soils could remain beneficial for control of weeds and root-knot nematode and supply of nutrients from floods and BNF.

Nonetheless rice will be increasingly produced within political, physical, economic, and social environments of less supply of irrigation water, increased costs for irrigation water, increased costs of labor, and income opportunities from crop diversification. This could in some areas change the way irrigated rice is grown; and changes in irrigation water management, crop establishment, and land preparation could alter the supply of soil nutrients and the need for fertilizer.

An ample supply of water for continuous soil submergence favors BNF, the supply of plant-available N and P from soil, and transport of nutrients to crop roots. The need of rice for fertilizer can change when a reduced supply of irrigation water does the following:

- Alters indigenous supply of nutrients from sources other than fertilizer.
- Reduces supply of water for transporting broadcast fertilizer into the crop root zone.
- Risks yield loss from water deficit.

For puddled soils, a reduction in irrigation water to 'safe soil drying' with no decrease in yield, as for AWD (Figure 1), is not expected to markedly alter BNF, indigenous nutrient supply, transport of nutrient to roots, and hence the need of rice for fertilizer. The nutrient best management practices are consequently expected to remain unchanged, but AWD might require more investment in weed control.

For non-puddled soils, a reduction in irrigation water use to 'safe soil drying' (Figure 1) with no decrease in yield could reduce BNF and alter availability of micronutrients. In such cases, the need for fertilizer N might increase, and the need for micronutrients such as zinc and iron might arise on high pH soil.

A reduction in irrigation water to 'unsafe soil drying' with a reduction in yield, such as for aerobic rice on non-puddled soil (Figure 1), alters crop demand for nutrients and indigenous supply of nutrients. The reduction in yield reduces the total amount of nutrient taken up by the crop; but the indigenous supply of N and P is reduced, and less K is supplied through irrigation water. The amount of fertilizer required to achieve a given target yield might increase because of the reduced indigenous nutrient supply and reduced input of K with irrigation water.

The efficiency of N fertilizer use can be increased by supplying N to match the crop's need for N during the vegetative growth phase and at panicle initiation. Prolonged soil drying with 'unsafe soil drying' could result in broadcast fertilizer remaining on the soil surface, not in contact with crop roots and prone to gaseous losses of N. Use of irrigation water to transport fertilizer into the crop root zone could increase fertilizer use efficiency.

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Chapter 10

Practices that simultaneously optimize water and nutrient use efficiency: Israeli experiences in fertigation and irrigation with treated wastewater

Asher Bar-Tal[1], Pinchas Fine[2], Uri Yermiyahu[3], Alon Ben-Gal[4] and Amir Hass[5]

Abstract

The Israeli experience regarding simultaneous application of water and nutrients is presented and discussed. The first section of the chapter deals with fertigation and the second section with irrigation with treated wastewater (TWW).

Fertigation theoretically allows precise application of nutrients spatially and temporally. The effects of management practices and soil properties on water quality and mineral transport in soils are presented. Crop nutrient requirement during the growing season and under different environmental conditions is described. Conceptual strategies to optimize synchronization of fertigation to both the physical and biological aspects of crop nutrient requirements are discussed. A summary of the benefits and concerns of fertigation practices is presented at the end of this section.

The characteristics and composition of TWW in relation to sewage source and the method and rate of treatment are presented. Osmotic and specific toxicity effects of high concentrations of salts from saline water or TWW on soil and crop are presented with suggested management practices to reduce salt stress.

The effects of applying TWW on availability of nitrogen, phosphate, potassium and trace elements to crops are presented. Specific considerations for each nutrient in relation to the use of treated water are discussed.

[1] Agricultural Research Organization, Bet Dagan, Israel, abartal@volcani.agri.gov.il
[2] Agricultural Research Organization, Bet Dagan, Israel, finep@volcani.agri.gov.il
[3] Agricultural Research Organization, Gilat Research Center, Israel, uri4@volcani.agri.gov.il
[4] Agricultural Research Organization, Gilat Research Center, Israel, bengal@volcani.agri.gov.il
[5] West Virginia State University, WV, US, amirhass@wvstateu.edu

Fertigation

Irrigation and fertilization are arguably the most important management factors in arid and semiarid climates, through which growers can manipulate crop yield and quality. Application of liquid fertilizers via drip irrigation systems called fertigation allows the benefits of nutrient application to crops in amounts and at times when they are most required by plants, and at locations where they are most likely to be absorbed by roots (Bar-Yosef, 1999; Mmolawa and Or, 2000; Hochmuth, 2003). A continuous supply of readily soluble nutrients via fertigation directly to the root zone maximizes economical yield and minimizes over-fertilization and pollution of groundwater by salt and nutrient leakage.

Water scarcity in arid and semiarid regions, for example in Israel and other Mediterranean countries, has led to expanded use of treated wastewater (TWW) for irrigation. Drip irrigation is considered as one of the barriers for pathogen contamination of agricultural products irrigated with TWW (Fine *et al.,* 2006; WHO, 2006; Paranychianakis *et al.,* 2011). The increasing use of TWW for irrigation has therefore provided an additional push to the replacement of traditional irrigation techniques with drip irrigation. The specific challenges and difficulties in fertigation with TWW are presented and discussed in section 10.2.

Since the early nineteen sixties, drip irrigation has spread all over the world and is now commonly adopted for irrigation in greenhouses as well as outdoor fields due to its water- and fertilizer-saving capabilities. The area under microirrigation is still relatively small, just 4% of global agricultural irrigated lands, but the rate of expansion is nearly linear and it is very rapid. In China, India, Japan and Australia the expansion rate is increasing. Global area covered by drip irrigation systems was about 66,000 hectares in 1874 and rose to 2.98 million hectares (Mha) in 1996 (Magen and Imas, 2003) and to 10.3 Mha in 2012 (International Commission on Irrigation and Drainage (ICID), 2012). The most dramatic expansions have occurred in China and India, the world's top two irrigators, where the area under microirrigation expanded 88fold and 111fold, over the last two decades. India is now the world leader with nearly 2 Mha. In India, the expected increase is 1 Mha per year. In most developing countries, microirrigation is used without fertigation and fertilizers are still being applied by broadcast dressing and banding. In Israel, where water availability limits crop production, microirrigation supplies about 75% of the total irrigated area. The integration of fertilization in microirrigation in Israel is probably a key factor in its success.

Water and mineral transport in soils from point sources

The distribution of water in soil irrigated by a point source is governed by soil properties and the discharge rate of the dripper. The movement of water in the soil from a dripper is driven by capillary and gravimetric forces. This creates a wet soil volume with soil varying in moisture content over soil depth (Bresler, 1977). The general geometry of the wetted soil volume below and around an emitter of a surface drip system is a symmetrical onion shape with the highest moisture close to the emitter and soil surface and gradual decrease with vertical and horizontal distances from the emitter down to a sharp wetting

front. The higher the discharge of the emitter, the shallower the depth of the wetting front, and bigger the horizontal distance from the emitter. In light textured soil with high hydraulic conductivity, the depth is greater and the horizontal distance is shorter than in heavier textured soil with lower hydraulic conductivity. The two principal driving forces that govern soluble ion and molecule movement in soil are convection and diffusion. Consequently, soluble ions and molecules with neutral charge move from the dripper toward the borders of the wetting front as shown in Figure 1. Soil type and discharge rate of emitters have influenced the distribution of volumetric salt content (Bresler, 1977). Under identical discharge rates, the lateral movement of salts in a sandy soil was about half that for a loamy soil and the downward movement was three times greater.
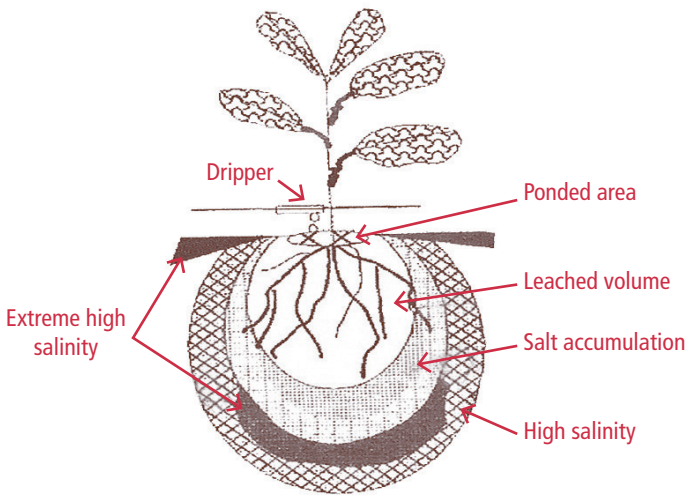
Figure 1. Salt distribution in the wetted soil volume below the emitter (adapted from Kremmer and Kenig, 1996).

When subsurface drip irrigation is practiced, the wetted volume is centered on the emitter and the water above and below the emitter is unevenly distributed with a longer vertical distance below the emitter than above it (Figure 2). Many studies suggest that root water uptake is related to root density and that root water uptake varies nonlinearly with depth in the soil profile (Hayhoe, 1981; Chandra and Rai, 1996). If soils are frequently irrigated, especially from the surface, they will remain relatively wet there and most of the root water uptake will then take place in the upper soil layers (Klepper, 1991). Coelho and Or (1999) characterized two-dimensional root distribution for drip irrigated corn plants. They fitted Gaussian distribution parametric models to the corn root length density (RLD) to produce two-dimensional root distributions that they compared to root water uptake (RWU) patterns as shown in Figure 2. Although it has been shown that actual water uptake patterns are a result of the complex interplay between RLD and other soil factors, such as water and nutrients, the distribution of RLD
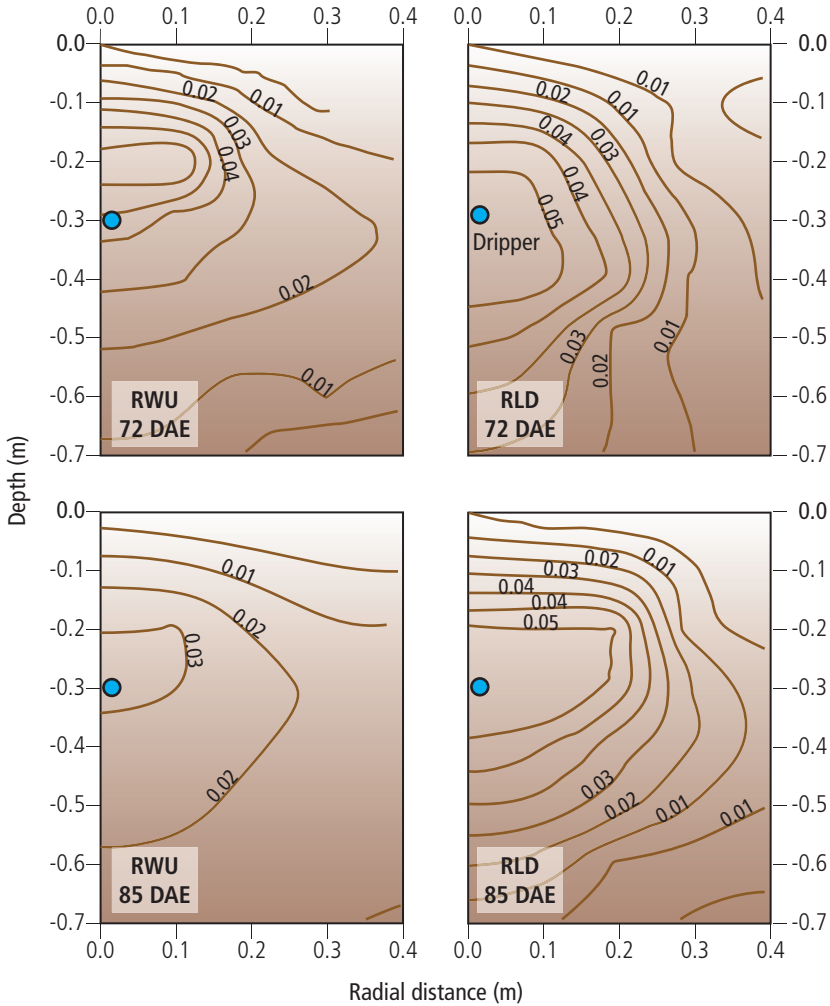
Figure 2. Normalized root lenght density (RLD) and root water uptake (RWU) values around a subsurface drip source buried under crop rows, 72 DAE (top) and 85 DAE (bottom) (adapted from Coelho and Or, 1999).

is still an important indicator of potential water uptake. A parallel between root density distribution and water distribution and uptake under drip irrigation is demonstrated in Figure 2.

Crop demand for nutrients

The demand for nutrients varies widely and dramatically during crop growth. Therefore, recognition of the crop demand for nutrients as a function of time (consumption curves) and environmental conditions is required for optimal fertigation management. The

nutrient consumption curve depends on the dry matter production curve, but there are differences between the two, which vary with developmental stage and between specific nutrients. There are considerable differences in uptake rate and in the time at which maximum consumption rate occurs, among crops and among varieties of the same species. In many cases, the consumption function is not monotonic, but exhibits sharp changes at critical physiological stages. Basically, the rate of nutrient requirement at each growth phase is associated with two predominant processes: (i) formation of new vegetative plant tissues; and (ii) formation of reproductive organs (flowers, fruits, seeds, etc.) (Bar-Yosef, 1999; Hochmuth, 2003; Epstein and Bloom, 2005).

Daily nutrient uptake rates can be derived from consumption curves, and those that result in optimum yield and product quality are crop-specific and depend on climatic conditions. Lack of attention to the changes in the uptake rate with time may lead to periods of over- or under-fertilization. Over-fertilization may enhance soil salinity, environmental contamination and vegetative development, whereas under-fertilization may result in nutrient deficiency and yield reduction (Bar-Yosef, 1999).

The rate of nutrient uptake by a leafy vegetable (lettuce) is characterized by an exponential curve, increasing sharply over time (Silber *et al.,* 2003), whereas that of fruit-bearing crops has been characterized by three periods: an exponential rate during initial vegetative growth, followed by a linear growth rate, and finally the senescence period as reproductive organs develop (Hochmuth, 1992). This consumption curve closely fits published measurements of nutrient uptake by determinant crops such as maize (*Zea mays* L.) and fruiting vegetables such as topped tomatoes (Tanaka *et al.,* 1974). When non-terminating plants like tomatoes and peppers were grown continuously under well-controlled climatic conditions their nutrient uptake rate grew steadily until production of the first fruit truss, and then became monotonic (Tanaka *et al.,* 1974; Bar-Yosef, 1999).

Extrapolation of known N, P and K uptake data to environmental conditions different from those specified should be done carefully, and treated only as a first approximation. For example, Xu *et al.* (2001) reported that the total consumption of N by pepper plants in the summer was 2.2-2.8 times higher than that in the winter, although the nutrient solution contained the same concentration of N. Absolute uptake of nutrients is more or less determined by growth and transpiration rates, but the uptake of individual nutrients depends more on the physiological stage of growth (Voogt, 2003).

Fertigation management

In this section we discuss the main fertigation and irrigation management factors that impact nutrient uptake by plants, root growth and chemical reactions in the soil rhizosphere that influence nutrient bioavailability and root growth. The factors that will be presented are the synchronization of fertilization with irrigation, irrigation frequency and the source of N.

Nutrient transport in the soil from an irrigating source to the root surface takes place by two simultaneous processes: convection in the water flow (mass flow), and diffusion along the concentration gradient (Tinker and Nye, 2000). Soil properties, crop characteristics and growing conditions affect the relative importance of each mechanism. The nitrate ion is minimally bound to solid phases, and NO_3^- is more mobile in soil as

compared to P and K which are more strongly sorbed onto surfaces. Consequently, the mobile NO_3 ion supply is taken up mainly through mass flow, whereas for less mobile elements such as P and K, diffusion is the governing mechanism (Claassen and Steingrobe, 1999; Mmolawa and Or, 2000; Tinker and Nye, 2000). Simulation and observation of nutrient uptake by plants showed that the volumetric water content had a strong impact on P, whereas NO_3^- was less sensitive (Bar-Tal *et al.*, 1994; Gahoonia *et al.*, 1994; Claassen and Steingrobe, 1999).

The distribution of the applied easily mobile forms of N, i.e. NO_3 and urea, is very sensitive to fertigation management and soil hydraulic properties. Cote *et al.* (2003) showed that applying NO_3 at the beginning of the irrigation cycle in the highly permeable coarse-textured medium could greatly reduce the risk of solute leaching in comparison to application at the end of the irrigation cycle.

Continuous application of orthophosphate through the irrigation water has been shown to be superior to the application of P in adequate quantities as basic fertilization (Ben-Gal *et al.*, 2003). Extractable P concentrations in the soil immediately surrounding a point source were found to be 20 to 25% higher in continuously irrigated soil as compared with pulsed irrigation (Figure 3). The biomass and leaf P concentration of corn plants grown

Volumetric water content * 100
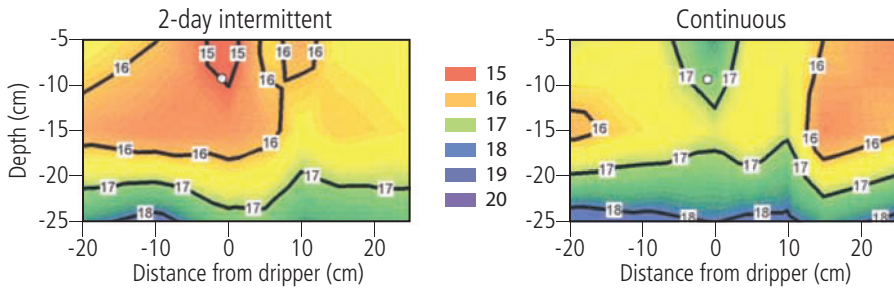
Bicarbonate extractable phosphorus (mg kg^{-1})
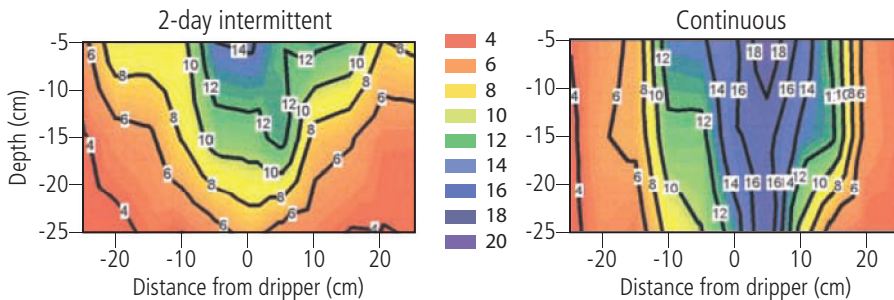
Figure 3. Water and phosphorous distribution under intermittent or continuous drip irrigation (Ben-Gal and Dudley, 2003).

under continuous fertigation were 20 and 25% greater, respectively for the continuous treatment compared to the pulse irrigation (Ben-Gal *et al.,* 2003).

Irrigation frequency is an important management factor in water supply. The beneficial effects of high-frequency irrigation were recognized some decades ago, and it is considered a useful tool for optimizing the root environment (Rawlins and Raats, 1975; Silber and Bar-Tal, 2008). When ions are supplied to the soil via the irrigating water their concentrations in the soil solution decrease with time due to adsorption onto solid phases and precipitation of insoluble compounds. Therefore, high concentrations of nutrients used in fertigation with low frequency irrigation lead to fluctuations from high or even excessive concentrations immediately after irrigation in the rhizosphere to deficit levels as time proceeds (Figure 4).

Reducing the time interval between successive irrigations may reduce variations in nutrient concentration and enable fertigation at concentrations approaching those required by the roots (Figure 4). The impact of fertigation frequency on the uptake of nutritional elements by plants follows the expected order of P > K > N (Kargbo *et al.,* 1991; Silber *et al.,* 2003; Xu *et al.,* 2004).
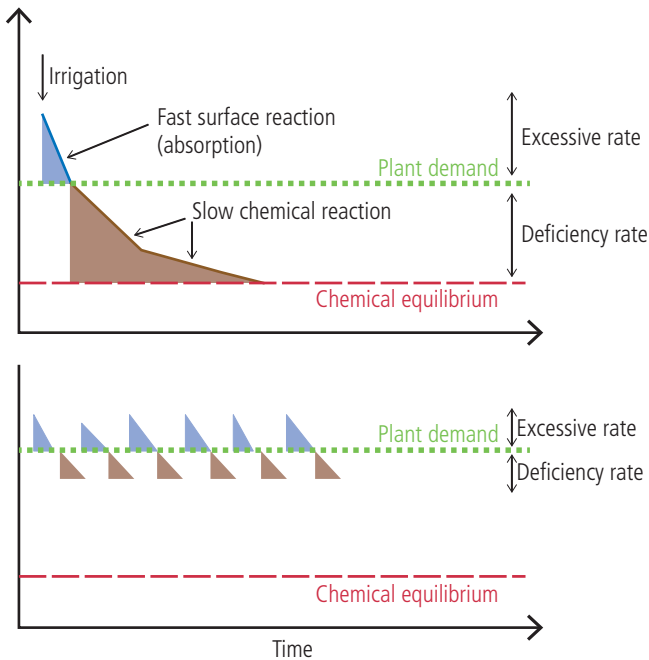
Figure 4. Schematic presentation of the time variation of nutrient concentration in the rhizosphere under conventional and frequent irrigation (a and b, respectively). Excess and deficiency rates correspond to nutrient concentration above or below plant demand, respectively; chemical equilibrium corresponds to nutrient concentration governed by equilibrium processes.

Irrigation frequency influences root system architecture and root length through two main mechanisms: (i) a direct effect on the wetting patterns and water distribution in the soil volume, which modulate root distribution and growth (Phene *et al.,* 1991; Coelho and Or, 1999); and (ii) an indirect effect on nutrient availability (Lorenzo and Forde, 2001), especially that of P, which significantly modifies root system efficiency (Lynch and Ho, 2005), including root hair density (Ma *et al.,* 2001) and root system architecture (Williamson *et al.,* 2001). It has been shown that yield gained under high irrigation frequency can be primarily related to increased availability of nutrients, especially P (Silber *et al.,* 2003). High correlation was obtained between yield and P concentration in leaves (Silber *et al.,* 2003, Xu *et al.,* 2004), indicating that the main effect of fertigation frequency was related to improvements in P mobilization and uptake.

Nitrogen source effects

There are two ionic forms of N taken up by plants: NH_4^+ and NO_3^-. The main effects of N source on plants are: ammonia toxicity, modification of the rhizosphere pH, availability of other nutritional elements, and incidence of physiological disorders such as chlorosis and blossom-end rot. Nitrogen source may affect the rhizosphere pH via three mechanisms (Bar-Yosef, 1999): (i) displacement of H^+/OH^- adsorbed on the solid phase; (ii) nitrification/denitrification reactions; and (iii) release or uptake of H^+ by roots in response to NH_4 or NO_3 uptake. This mechanism (iii) may be very effective because it affects a limited volume in the immediate vicinity of the roots (Gahoonia and Nielsen, 1992; Bloom *et al.,* 2003). The extent of the pH alterations caused by the three mechanisms described above depends on soil properties, wetted volume, plant activity, and the environmental factors that affect nitrification rate.

The rate of NH_4^+ uptake by most plants is faster than that of NO_3^- (Marschner, 1995). However, the rate of nitrification in soil is rapid and therefore the NH_4^+ concentration diminishes quickly. Frequent fertigation by drip irrigation maintains the NO_3/NH_4 ratio (R_N) in the soil similar to that in the irrigation water. Reduction of the medium pH, driven by NH_4^+ nitrification and root excretion of protons, can be used as a tool for overcoming growth disorders induced by micronutrient deficiencies, such as chlorosis and "little leaf" or "rosette" (Silber *et al.,* 1998; Savvas *et al.,* 2003).

Nitrogen source has a significant direct effect on numerous physiological processes in plants (Marschner, 1995; Mengel and Kirkby, 2001; Epstein and Bloom, 2005). R_N affects the apoplastic pH and, consequently, Fe^{III} reduction and mobilization in plants (Kosegarten *et al.,* 1999; Zou *et al.,* 2001). It is well documented that high NH_4^+ concentration and high R_N enhance the incidence of blossom end rot in vegetable fruits through its influence on Ca uptake (Ho *et al.,* 1993; Bar-Tal *et al.,* 2001; Adams, 2002).

Advantages and disadvantages of fertigation

The main advantages of fertigation over irrigation combined with broadcast or banding fertilization can be summarized as follows: (a) The application of nutrients and water is accurate and uniform under all circumstances; (b) application is restricted to the wetted area, where root activity is concentrated; (c) the amounts and concentrations of specific nutrients can be adjusted to crop requirements according to the stage of

development and climatic conditions; (d) fluctuations in nutrient concentrations in soil over the course of the growing season are reduced; (e) it enables irrigation with higher saline water than other irrigation methods; (f) crop foliage is kept dry, thus retarding the development of plant pathogens and avoiding leaf burn; (g) energy use is reduced by the avoidance of broadcast operations and because of the lower water pressure required for trickle irrigation relative to sprinkler systems; (h) soil compaction and mechanical damage to crops are reduced because there is less tractor traffic; (i) it enables convenient use of compound, readymixed and balanced liquid fertilizers, with minute concentrations of minor elements which are otherwise very difficult to apply accurately to the field; and (j) it is the safest method for irrigation with sewage effluent.

Fertigation also has some disadvantages, which can be summarized as follows: (a) The necessity for additional capital outlay, since the installation of drip systems with fertilizer injection devices, and fertilizer tanks, is more expensive than that of sprinkler irrigation systems; (b) safety considerations, especially in preventing the back-flow of chemicals into the water supply; (c) increased risk of emitter clogging; (d) accumulation of salts in the wetting front; and (e) reduction of the root volume.

Irrigation with treated wastewater

The future of irrigated agriculture is threatened by existing or expected shortage of freshwater, especially in semiarid and arid regions. This shortage results mainly from the ever-increasing demand put upon water resources by the rapidly growing world's population and its improving standard of living. The constant increase in population and in water use per capita have led to an ever-growing volume of municipal sewage water that needs to be disposed of or reused in a safe manner.

Irrigation with TWW offers utilization of an otherwise non-exploited water and nutrient resources. The major issues of irrigation with TWW are discussed in the following sections.

Characteristics and composition of TWW

Wastewater effluent is recognized as a water resource for irrigated agriculture and a substitute for potable water in semiarid and arid regions of the world (Pettygrove and Asano. 1985; Asano, 1998; Feigin *et al.,* 1991; US-EPA, 2004, 2006; Levy *et al.,* 2011). Municipal wastewaters (WW) are primarily of domestic origin, which include discharge from residential areas, commercial areas and institutional facilities (schools, hospitals, etc.; Iannelli and Giraldi, 2011). The constituents of domestic wastewaters are often similar all over the world, yet with larger loads of some chemicals (e.g., housekeeping products) and pharmaceuticals and personal care products in developed countries, and higher organic loads (in terms of chemical oxidation demand (COD)), and less extent of dilution in countries of more arid regions (Feigin *et al.,* 1991). Failure to separate industrial wastewater from domestic sources of wastewater might enrich municipal wastewater with unwanted constituents whose identity depends on the specific industries involved.

Table 1. Constituents of wastewater and of two secondary effluent types*

Component	Units	Raw	OPE	MBTE	SAT (tertiary)	Ceiling – long-term irrigation[2]	Full strength nutrient solutions[3]
pH		7.24	7.9	7.65	8.2		5-7
EC_{25}	dS m^{-1}	1.87	1.91	1.71	1.65	1.4	0.5-2.7
TSS (105°C)	mg l^{-1}	434	127	52	<1	10	
COD	mg l^{-1}	883	428	72	6	100	
OC	mg l^{-1}	173	115	25	1.8		
BOD_5	mg l^{-1}	395	134	24	<0.5	10	
Alkalinity (as $CaCO_3$)	mg l^{-1}	394	405	308	269		
N_{total}[4]	mg l^{-1}	65	54	25	2.98	25	100-200
NH_4-N	% of N_{total}	62	39	65	1	10 (mg l^{-1})	10-70
P_{total}	mg $^{-1}$	15	17	5.1	0.05	5	30-50
Cl	mg l^{-1}	318	350	318	296	250	5
SO_4	mg l^{-1}	77	91	77	97		48-224
Ca	mg l^{-1}	62	85	73	100		100-200
Mg	mg l^{-1}	39	32	33	16		30-70
Na	mg l^{-1}	229	257	176	202	150	
SAR	(mmol l)$^{-0.5}$	3.2	3.2	2.4	4.9	5.0	
K	mg l^{-1}	33	36	21	25		100-200
Fe	mg l^{-1}	1.96	0.25	0.31	0.037	2.0	2-12
Zn	µg l^{-1}	935	166	119	70 (650)	2000	50-100
Cu	µg l^{-1}	295	34	15	6	200	10-100
Mn	µg l^{-1}	85	59	41	14 (640)	200	500-2000
Mo	µg l^{-1}	10	5	5	<3	10	5-200
B	µg l^{-1}	550	590	510	190	400	200-400
Ni[5]	µg l^{-1}	62	30	21	4	200	
Co[5]	µg l^{-1}	4	<3	<3	<3	50	
Se[6]	µg l^{-1}	<1	1	<1	<2	20	
Cr[5,6]	µg l^{-1}	214	14	14	<3	100	
Cd	µg l^{-1}	4.6	<0.3	<0.2	<0.2	10	
Pb	µg l^{-1}	32	<5	<4	5	100	
Hg	µg l^{-1}	<0.5	<0.5	<0.1	<0.1	2	

*Based on the Greater Tel-Aviv Region, wastewater treatment plant, Israel; Data are averages of multiple samplings during the year at 19 locations within the WWTP. Composite samples were collected from the raw sewage and MBTP whereas grab samples were taken from the ponds
[1]Data extracted from the 1995 records of the Tel-Aviv (Israel) WWTF (Soffer *et al.*, 1996): Raw: incoming wastewater; OPE: oxidation ponds effluent MBTE: mechanical-biological treatment effluent; SAT (soil aquifer treatment) data after Ickeson-Tal *et al.* (2008) Soreq recharge basins (38 years recharge), well 54. Mn and Zn concentrations are high (in parentheses) and yet increasing owing to aquifer material dissolution. [2]New Israeli regulations («Inbar committee»); values are monthly arithmetic averages; [3]After Jones (2005); [4]$N_{total} = N_{kjeldhal}$, except for «After SAT» where this is mostly (99% NO_3-N); [5]Recognized as essential to plants but seldom added; [6]Essential in human diet.

Typical compositions of primarily domestic municipal WW and of secondary TWW are presented in Table 1 (Fine *et al.*, 2002; Fine and Hass, 2007).

The secondary effluent is the treatment product of either facultative oxidation ponds or mechanical-biological treatment (MBT) of municipal wastewater. Also presented in Table 1 are the updated Israeli-allowed values pertinent to TWW constituents (for other countries please see Paranychianakis *et al.*, 2011). A 30-day residence in an oxidation ponds effluent (OPE) was found to reduce concentrations of suspended solids, total and fecal bacteria, N and trace elements. The 10% increase in concentration of conservative ions, such as Cl$^-$ (Table 1) suggests concentration due to evaporation during the 30-day retention time (a 10% increase in concentration is expected using average potential evapotranspiration value of 4.9 mm day^{-1}, based on 1988 – 2000 mean daily evaporation values [Israel Meteorological Service, 2007] and assuming a 1.5 m deep pond). MBT with nitrification-denitrification process showed considerably higher efficacy in reducing most WW constituents compared to OPE. If final use of the effluent is as irrigation water for crop production, the substantial reduction in macronutrients and micronutrients during the MBT may be viewed as an unnecessarily excessive treatment. Yet, the contribution of MBT to the reduction in heavy metals and OC content is invaluable and cannot be overlooked. Biological treatment is not expected to reduce salinity components (Na, Cl and B). Hence, some Israeli long-term irrigation ceiling concentrations (Table 1) are sustainable only if a combined soil-aquifer treatment (and ensuing dilution) and/or desalination (at source or after WWT) is included.

Many sources of B (detergents, seawater) can be avoided or treated in the source water using available legislative and technological tools (Tarchitzky *et al.*, 2006). In Israel, recognition of the problem of high B in TWW destined for irrigation, lead to policies and regulation insuring a ceiling of 0.4 mg l^{-1} B in effluent (Tarchitzky *et al.*, 2006; Yermiyahu *et al.*, 2007). Most notable were legislations restricting B from laundry detergents and demand for post-process removal of B in seawater desalination plants providing water to municipalities (Yermiyahu *et al.*, 2007). Desalination technology is becoming increasingly attractive and offers an opportunity to remove salts in source (municipal) water and to leave agriculture with a higher quality water that will lead to higher yields and lower environmental impact (Ben-Gal *et al.*, 2009).

The main purpose of WW treatment is to reduce pathogens to tolerable levels (WHO, 2006). The WW is treated at various levels to remove pathogens, organic matter and nutrient elements, with regulations and guidelines based on public-health assurance criteria while also relying on economic and technological capabilities (US-EPA, 2004; Paranychianakis *et al.*, 2011; Shuval, 2011). In the more developed countries, WW treatment is technology-based and the properties and composition of WW products (TWW and sludge) are determined more according to capabilities and do not often consider ramifications on options for the effluent's use under various agricultural scenarios (US-EPA, 2004, 2006; WHO, 2006; Fine *et al.*, 2006; Inbar, 2007; Fine and Hadas, 2012). Less demanding sewage treatment would preserve more of the incoming fertilizer content and bioavailability (e.g. N). Such an approach is beneficial to agronomic end users as it provides an additional source of nutrients. Moreover, reducing the intensity of the treatment at the WWTP will reduce on- and off-site greenhouse gas

(GHG) emissions (Bogner *et al.,* 2007; Fine and Hadas, 2012). It has been suggested that WW reuse regulations should consider the additional pathogen (and pollutants) removal gained by appropriate agricultural utilization of TWW (WHO, 2006; Fine *et al.,* 2006; Shuval, 2011). For example, the Israeli regulations for TWW irrigation follow a reduced risk approach. This is achieved either through advanced treatment of WW to meet fecal coliform (FC) limits (< 10 cfu100 ml^{-1} for unrestricted irrigation), or by a combination of appropriate treatment levels and on-farm preventive measures. The latter approach relies on a wide range of FC barriers that are taken into consideration, such as TWW quality, crop type, cropping methods, harvesting and irrigation methods, and the nature and intended use of crop (Table 2; Fine *et al.,* 2006; Paranychianakis *et al.,* 2011).

Risks and challenges for irrigation management of TWW

Contaminants in TWW present risks and challenges for water management that are manifested starting in distribution and irrigation systems, continue to the soil and ultimately reach crops and plants (Asano, 1998).

Irrigation systems utilizing TWW and/or chemical fertigation can be impaired by fouling of pipes and equipment and of clogging of emitters. Causes for clogging can be physical, chemical or biological. Physical clogging occurs when suspended solids block narrow flow paths. Chemical clogging occurs subsequent to precipitation of soluble salts, most often carbonate, phosphate or sulfate. Biological causes of clogging are related to biofilm formation and algal or bacterial growth. Organic matter and nutrients in TWW are the key causes of biofilms which can affect all components of the distribution system and clog emitters. Definitive problems of fouling/clogging are often due to combined effects of these causative agents. Clogging becomes more probable and problematic as flow paths for water become smaller and therefore prevention of scaling and clogging are particularly critical in microirrigation systems. Prevention of clogging is possible but requires attention and investment and must be designed to specific water quality. Suspended particles can be filtered out physically. Algal growth can be controlled chemically. Biocides can be injected into the system to restrict microbes and biofilm production. Acids and antiscalants can be dosed to reduce scale formation. Flushing of laterals is often effective in clearing potential clogging agents from the system (Doseretz *et al.,* 2011).

Some contaminants pass through the distribution systems as small particles and dissolved matter. They reach the soil with the water where they can accumulate and affect soil physical properties. Degradation of soil physical properties may be caused by relatively high loads of dissolved organic matter (DOM), suspended solids, sodium and relative concentration of sodium to other cations, and salinity in general (Levy and Assouline, 2011). Irrigation with TWW can intensify clay swelling and dispersion due to high sodium adsorption ratio (SAR) and DOM. Sodic conditions, especially when overall salt levels are low, increase sensitivity of clay soils to swelling and dispersion. These, in turn adversely affect soil hydraulic properties by reducing conductivity of the soil and negatively affecting infiltration and distribution of water. Recently, soils irrigated over time with TWW have been found to become increasingly hydrophobic (Levy and

Assouline, 2011). Water repellency is undesired as it reduces initial infiltration upon wetting and leads to non-uniform flow and distribution of water in the soil (Levy and Assouline, 2011).

TWW often has high salt concentrations compared to freshwater. Plants are negatively affected as the concentration of salts in the root zone increases. Response to salinity is dependent upon all the variables influencing the root environment, uptake by the plant, and physiological behavior. These variables include ion composition and concentration in soil solution, crop type, cultivar and growth stage, climate, and length of exposure. The composition and concentration of the soluble salts in soil solution are known to directly influence plant growth, by creating osmotic imbalance and via specific physiological toxicity of ions.

The dominant salt minerals in TWW are Na and Cl but these can be accompanied by Ca, Mg, SO_4, K and HCO_3 ions. When these ions increase in soil solution, both osmotic potential decreases (leading to reduced water uptake) and excess ion levels leading to toxicity are likely to occur (Bernstein, 1975). Plant response time for osmotic effects is rapid (seconds to minutes). Toxic responses can be rapid as well, especially in cases where the mechanism for toxicity occurs in the roots, but responses due to toxic effects often materialize only following accumulation in shoots – a process taking much more time (days to months) (Munns, 2002). Toxicity is mostly an issue with NaCl salt. Sensitivity to Cl and Na ions is crop-specific, with individual crops showing sensitivity to either or both Na and Cl (Bernstein, 1975).

Management of water containing high concentrations of salts must consider both leaching requirements (water applied to remove salts from the root zone) and crop response to stress conditions caused by combinations of all possible stress-causing factors. Field and lysimeter experiments were conducted in Israel to investigate the response of vegetable crops irrigated with saline water to irrigation levels (Shani *et al.,* 2007; Ben-Gal *et al.,* 2008 , 2009) and to elevated concentrations of B (Ben-Gal and Shani, 2002; Yermiyahu *et al.,* 2008). The quality of water in the experiments was designed to represent across-the-scale expected qualities of recycled municipal wastewater. When salinity is negligible, yield increases as a function of increased application of water to a crop, up until the point that the demand for evapotranspiration is satisfied. When salts are present, they depress water uptake and growth and, therefore, additional water application is accompanied by a positive yield response. The mechanism for this is leaching of salts from the soil and maintenance of a relatively salt-free environment for root activity. Irrigation water salinity decreases transpiration and biomass production of crops. The extent of the salinity response is dependent upon the level of leaching of salts from the root zone. Application of saline water to the soil, exceeding the quantity used by the crop for transpiration, is successful in improving conditions for water uptake and growth (Figure 5). The addition of such water has a higher relative benefit when the salinity of the water and the sensitivity of the crop increase. Lysimeter, field, and modeled experimental results in dry regions of Israel suggested that potential economic benefits from increased yields exist for irrigation application rates reaching more than 200% of the ETp for a high value but a relatively salt-sensitive crop like bell pepper (Figure 5). Leaching fractions were seen to increase as a result of reductions

Table 2. The number and type of barriers to pathogen transfer that are recommended by the Israel Ministry of Health according to crop type and effluent quality (Fine et al., 2006; Paranychianakis et al., 2011) (adapted from Halperin, 1999; Fine et al., 2006)[1].

Crop	Dis.[1]	Number of barriers required				Value of barrier (by type and practice)				
		Low input[2]	Low input + >10 days detention[3]	High input[4]	Unrestricted irrigation[6]	Aerial distance from drip-emitters	Plastic ground cover	Sub-surface drip.	In-edible pill or shell	Cooking obligatory
Leafy vegetables, strawberry		Prohib	Prohib	Prohib	only					
Vegetables eaten-fresh grown above ground (pepper, tomato, cucumber, paprika, and zucchini)	+	Prohib	Prohib	2	0		1	2		
Cooked vegetables with rind (eggplant, pumpkin)		Prohib	Prohib	2	0		1	2	1	1
Cooked vegetables grown in the ground (potatoes)		Prohib	Prohib	2	0					1
Peanuts		Prohib	Prohib	2	0				1	
Eaten-fresh vegetables grown in the ground (carrot, onion, radish)	+	Prohib	Prohib	2	0					
Beans	+	Prohib	Prohib	2	0		1	2		1
Vegetables with rind (watermelon, melon, peas)	+	Prohib	Prohib	2	0		1	2	1	
Artichokes		3	2-3	2	0	2	1	2		1
Corn (edible)		3	2-3	2	0	2	1	2	1	
Citrus		3	2-3	2	0	2	1	2	1	
Citrus, irrigated with pulsators or under-leaf sprinklers		3	2-3	2	0	1			1	
Citrus with edible peel (Chinese orange)		3	2-3	2	0	2		2		
Nuts, almonds, pomegranate, pistachios		3	2-3	2	0	2		2	1	
Deciduous trees (apple, prune, plum, pear, peaches, apricot) and cherry		3	2-3	2	0	2		2		
Tropical fruits (mango, avocado, persimmon)		3	2-3	2	0	1	1	2	1	
Tropical fruit with cutting of the lowest leaves		3	2-3	2	0	2	1	2	1	
Grapes with high trellis		3	2-3	2	0	2		2		
Grapes with regular trellis		3	2-3	2	0	1	1	2		

Crop	Dis.[1]	Number of barriers required				Value of barrier (by type and practice)				
		Low input[2]	Low input + >10 days detention[3]	High input[5]	Unrestricted irrigation[4]	Aerial distance from drip-emitters	Plastic ground cover	Sub-surface drip.	In-edible pill or shell	Cooking obligatory
Grape with no trellis	+	Prohib	Prohib	2	0		1	2		
Cactus fruits		3	2-3	2	0	2	1	2	1	
Dates		3	2-3	2	0	3	1	2		
Olives		3	2-3	2	0	1	1	2		1
Flowers		3	2-3	2	0	1	1	2	1	

[1] Disinfection: (+) sign denotes disinfection is an obligatory barrier

[2] Low input treatment: BOD > 60 mg l^{-1}, TSS > 90 mg l^{-1}; e.g., oxidation pond effluent with detention time ≤ 10 days.

[3] Medium input treatment from oxidation ponds effluent with detention time >10 days (BOD 20-60 mg l^{-1}, TSS 30-90 mg l^{-1}).

[4] High-quality effluent from MBTP or equivalent (BOD: 20 mg l^{-1}, TSS: 30 mg l^{-1}).

[5] Effluent suitable for unrestricted irrigation: wastewater treatment by any of the following methods: deep sand filtration, prolonged ponding (≥ 60 days) or dilution in reservoir to <10% of the water (FC ≤10/100 ml and turbidity ≤5 NTU or TSS ≤ 10 mg l^{-1} and 1 mg l^{-1} residual chlorine at the site of irrigation
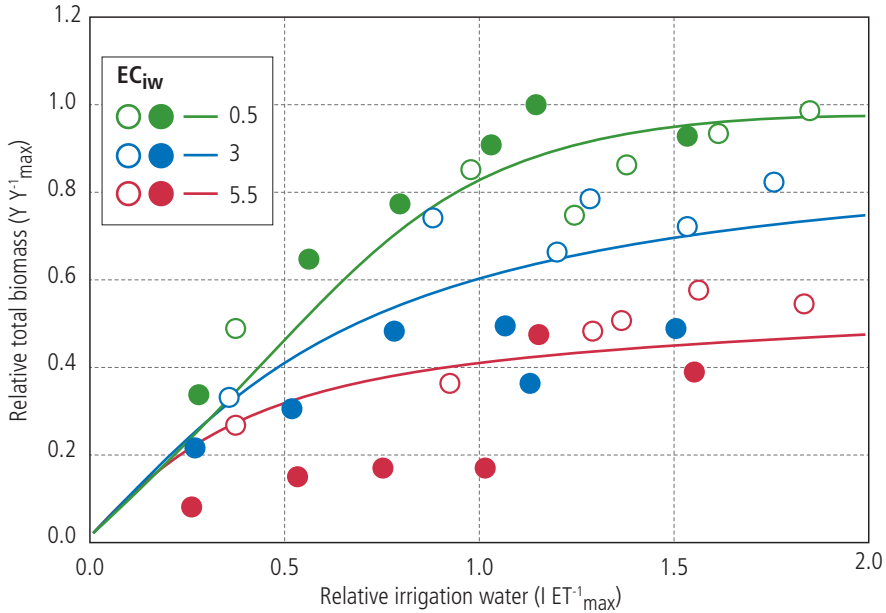
Figure 5. Relative total biomass production of peppers (Yield normalized to maximum yield) as a function of irrigation application level for three irrigation water salinity (ECIW (dS m^{-1})) levels. Symbols are experimental measurements from two seasons (open fall, closed spring) and lines are results from the analytical ANSWER model (Ben-Gal *et al.*, 2008; Shani *et al.*, 2007).

in transpiration caused by increases in salinity (Dudley *et al.*, 2008). Figure 5 shows that while total yield is limited by source water salinity and sensitivity of the crop, as salinity increases, so does the marginal effect of increasing water application rate over ET requirements. In other words, when the water is salty, higher application means higher yield.

Decision making by growers benefits from consideration of soil-crop-climate specific predictions of yield as a function of irrigation water quality and quantity (Figure 6). For example, a farmer in a desert region irrigating with saline water (EC = 3 dS m^{-1}) cannot expect to reach greater than 70% of the potential yield for a pepper crop even with exorbitant rates of water application. By choosing a more tolerant crop, melon, the farmer can achieve 90% of potential yield with the same water that yielded 70% of pepper yield.

Due to the need for leaching, long-term irrigation with saline water under arid conditions is problematic. Sustainable cultivation must provide for collection and disposal of the leached salts and water or, alternatively, reduce the leaching. Reduced leaching is only possible through cultivation of highly tolerant crops or via the reduction of water salinity prior to irrigation (Ben-Gal *et al.*, 2008; Ben-Gal *et al.*, 2009; Shani *et al.*, 2007).
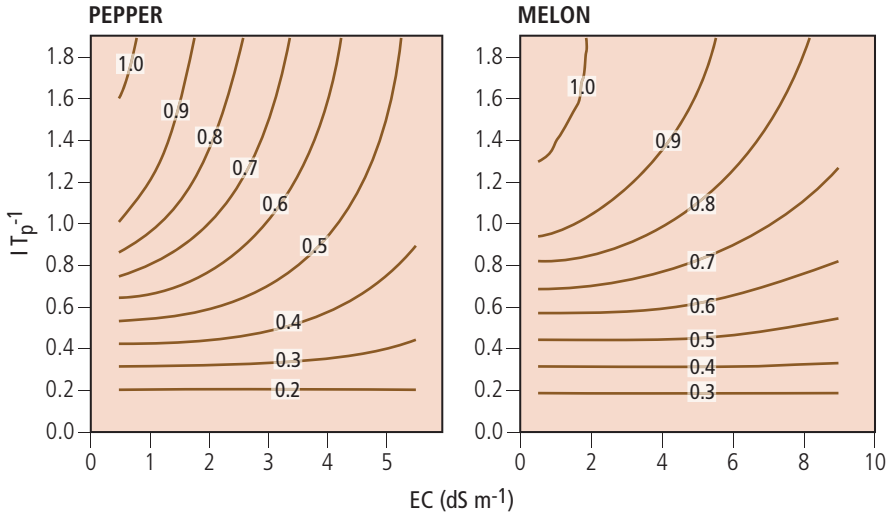
Figure 6. A compensation presentation of Iso-yield curves for irrigation water salinity (EC) and applied irrigation water quantity relative to climate demand (I Tp^{-1}) for pepper and melon crops. Curves were computed using the ANSWER model (Shani *et al.*, 2007). Isolines show 10% increases in relative yield.

Possible contribution of treated wastewater components to availability of nutrients

TWW may contain high concentrations of nutrients; therefore, irrigation with TWW is a means to recycle nutrients as well as water. The end user can gain additional benefit from irrigation with TWW by saving fertilizer and maintaining soil fertility. As the nutrients in TWW are applied to the field with the water, fertilization is similar to fertigation with the same advantages. Unlike regular fertigation, the grower does not control the amount of nutrients supplied by TWW and therefore there is a risk of overdose application and challenges in synchronization of application with the requirements of the crops. Recycling nutrients through irrigation with TWW is an additional benefit to the environment and society by reducing greenhouse gas emissions otherwise produced by manufacturing and distribution of chemical fertilizers (Fine and Hadas, 2012). However, overdose of nutrients with TWW irrigation combined with regular fertilization or low efficiency of the nutrients in the TWW may lead to environmental pollution, through accumulation in soil, runoff to water reservoirs and leaching to groundwater. The main nutrients having concentrations in sewage water higher than in the original freshwater are N, P and K. Wastewater and TWW contain N and P in organic forms that do not exist in freshwater. Therefore, the plant availability of N and P applied by irrigation with TWW and their fate in the environment are different from those of N and P fertilizers (Bar-Tal, 2011; Bar-Yosef, 2011). Irrigation with TWW

may also have strong impact on micronutrient availability to plants and contamination of the environment. The main issues of efficient supply of N, P and micronutrients with TWW and the possible environmental problems due to irrigation with TWW are discussed below.

Nitrogen

Municipal wastewater contains high concentrations of organic and mineral N, ranging between 20 to 100 mg l^{-1} (Feigin *et al.,* 1991). The concentration of N in TWW decreases with the progress in the treatment level from primary to secondary, and is decreased significantly further during tertiary treatment during which N is removed from the effluent by nitrification and denitrification processes (Iannelli and Giraldi, 2011). Consequently, total N in TWW used for irrigation can range from 5 to 60 mg l^{-1} (Feigin *et al.,* 1991). Tarchitzky *et al.* (2006) reported that the average concentration of ammonium-N and total N (organic and mineral) in TWW used for irrigation in Israel was 23 and 31 mg l^{-1}, respectively. For some crops, N added to soils through TWW irrigation can even exceed the amount commonly applied via fertilization with freshwater (Feigin *et al.,* 1991). The major concerns in using TWW as a source of N are: 1. Environmental pollution hazards from N downward leaching or runoff, 2. Nitrogen losses by emission of gasses, and 3. Low availability of mineral and organic N in the TWW to crops. The main processes that influence N availability and its environmental pollution hazards are the chemical transformations of the added inorganic and organic N in the soil.

Nitrogen mineralization is the production of inorganic N from organic N. NH_4^+ becomes the dominant N form shortly after irrigation with TWW due to the high rate of organic N mineralization: 0.3, 0.4 and 1.1 wk^{-1} in sandy loam, loess and calcareous clay soils, respectively (Zhou *et al.,* 2003). The fate in soil of the NH_4^+ applied with TWW is affected by adsorption and fixation processes, nitrification and loss of gases. Adsorption governs NH_4^+ concentration in the soil solution for a short period of a few days after wastewater application (Phillips, 2002; Fernando *et al.,* 2005). The sorption and capacity of soils for NH_4^+ were found to increase in soils irrigated with liquid swine waste (Fernando *et al.,* 2005). Consequently, the risk of NH_4^+ leaching in soils irrigated with TWW is reduced by the enhanced sorption and fixation mechanisms.

The governing reactions and the environmental conditions that affect NH_3 volatilization from inorganic fertilizers and organic sources applied to soil have been reviewed in the last decade by Kissel *et al.* (2008) and Francis *et al.* (2008). Ammonia evolution is a function of its concentration in solution, which is governed by the NH_4^+ concentration and pH of the solution. The major factor that influences NH_3 volatilization from soils applied with different livestock slurries is the slurry infiltration depth (Sommer *et al.,* 2006). The NH_4^+ applied with TWW irrigation percolates into the soil and is therefore expected to be less exposed to volatilazation. The order of potential N losses through ammonia volatilization in irrigation systems is sprinkler>surface drip irrigation>subsurface drip irrigation. Therefore, N loss through ammonia volatilization from TWW irrigation is usually low and can be minimized by proper management.

Although the most common form of mineral N in effluents is NH_4^+, due to the rapid nitrification process, nitrate is the main mineral N found in neutral to calcareous soils of fields irrigated with TWW (Feigin *et al.,* 1984; Master *et al.,* 2004; Tarchitzki, 2006). In some acid soils irrigated with TWW, NH_4^+ was found to be the dominant N form (Livesley *et al.,* 2007) probably due to the decrease in the nitrification rate as the pH declines below the optimal condition at 7.5 (Kyveryga *et al.,* 2004). However, Phillips (2002) reported a rapid nitrification rate of ammonium from piggery wastewater in two sites in Australia where the pH ranged from 4.4 to 6.4.

High levels of nitrite (NO_2^-) in soil solution have been reported following TWW irrigation (Master *et al.,* 2003, 2004). Possible reasons for these findings are the higher sensitivity of nitrite oxidizing bacteria than the NH_4^+ oxidizers to high NH_4^+ levels (Nakos and Wolcott, 1972), the combined effect of the elevated NH_4^+ concentration and high pH (Burns *et al.,* 1996), and the effect of the increase in osmotic pressure and chloride concentrations (Darrah *et al.,* 1987). Other possible factors for the accumulation of nitrite in soil irrigated with TWW are the presence of dissolved organic matter with low molecular weight that delays the oxidation of nitrite (Stueven *et al.,* 1992) and oxygen stress created by the consumption of oxygen for decomposition of the TWW organic matter (Friedman and Naftaliev, 2012). Consequently, nitrite concentration in soil should be monitored when sensitive crops are irrigated with TWW.

Nitrogen losses by emission as the N oxy gases (NO and N_2O) and N_2 may reduce the efficiency of the N supplied through irrigation with rich N TWW (Bhandral *et al.,* 2007). However most studies indicate that the quantities of applied N losses as gasses from TWW irrigated soils are relatively small (Smith and Bond, 1999; Tozer *et al.,* 2005). The loss of these gases can be a result of denitrification or nitrification (Master *et al.,* 2003). Denitrification is anticipated to increase in heavy and poorly drained soils irrigated with low-quality TWW with high organic matter content. Greenhouse gas emissions due to denitrification (N_2O) are a potential problem in using TWW for irrigation.

There are very few direct measurements of the amount of N taken up by plants from TWW. Feigin *et al.* (1981) demonstrated, in a pot study employing ^{15}N enrichment, that the availability of N supplied with TWW was not different from N supplied by fertilizer with freshwater. There is a lot of indirect evidence from field experiments indicating that the response to N in TWW and N uptake of various crops is not different from that for applied inorganic fertilizer N (Barton *et al.,* 2005; Paranychianakis *et al.,* 2006; Jacobs and Ward, 2007). Bar-Tal *et al.,* (2011) reported in a literature review that most of the published works reported positive yield response and increase in leaf N or total N uptake to irrigation with TWW.

Irrigation with TWW increases the threat to groundwater quality from uncontrolled leaching of various constituents, including soluble organic matter, salts and nitrates (Ronen and Magaritz, 1985; Amiel *et al.,* 1990; Fine *et al.,* 2002), and may result in significant economic damage (Haruvy *et al.,* 2000). Since the major components of N in TWW are ammonium and dissolved organic N, N leaching under irrigation with TWW should be slower than under fertigation with nitrate. Under conditions of rapid nitrification, the transport and leaching of N as nitrate in soils under irrigation with TWW might be rapid (Kurtzman *et al.,* 2013). Downward movement of N and higher

inorganic N concentrations below the root zone were recorded in several long-term field experiments conducted in Israel to examine the possibility of minimizing N leaching from TWW irrigation of citrus and field crops (Figure 7). Although the dissolved
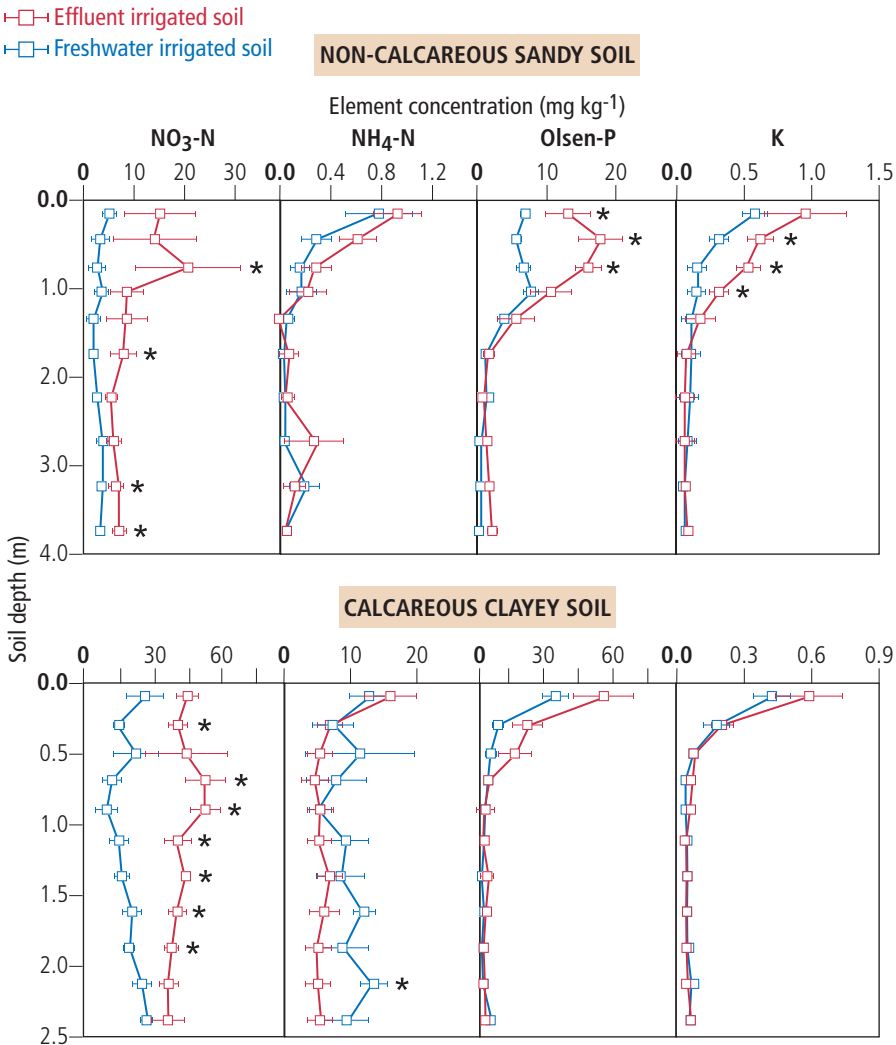
Figure 7. Concentrations of NO_3–N, NH_4–N, Olsen P, and K in the noncalcareous, sandy soil from the coastal plain site and in the calcareous, clayey soil from the Yizre'el Valley site irrigated with secondary treated wastewater or fresh water as a function of soil depth. Bars indicate two standard errors and asterisks indicate significant differences ($P < 0.05$) between treatments for each depth and soil. Note: scales on the y and x axes differ between sites (adapted from Lado *et al.*, 2012 SSSAJ 76:1358-1369).

organic N (DON) can be adsorbed by soil colloids (Kaiser and Zech, 2000), it has been found to be more mobile in soils than ammonium (Barton *et al.,* 1999; Singleton *et al.,* 2001; Zhou *et al.,* 2003). Thus, irrigation with TWW containing high DON could be a threat to the environment especially under poor drainage conditions.

When considering secondary effluent as an N source, the amount and timing of nutrient uptake by the crop have to be considered. Minimizing the leaching of TWW N in irrigated field crops and trees was achieved by accounting for the TWW-N in the fertilization application and by optimizing the irrigation volume (Fine *et al.,* 2002; Adeli *et al.,* 2003). Runoff and horizontal transport of excess N from TWW might pollute above-ground water resources. In a study of a land-based municipal TWW irrigation scheme in which an amount of 4.68 t N ha^{-1} was applied over 11 years (426 kg N ha^{-1} yr^{-1}) to wetland and forest systems, the transport of effluent N via runoff was estimated as 263 t (29%) of the applied N (Tozer *et al.,* 2005).

Phosphorus

Raw sewage water contains high concentrations of organic and mineral P, the range depending on the water source. The P content in raw municipal sewage water is wide, ranging from 4 to 36 mg l^{-1} (Feigin *et al.,* 1991). Secondary (biological) treatment has only a slight effect on total P concentration in TWW (Feigin *et al.,* 1991). The concentration is reduced to very low values of 0.1 to 0.2 mg l^{-1} (Feigin *et al.,* 1991; Fine and Hadas, 2012), by various tertiary treatments: (a) addition of alum or lime designed to coagulate suspended solids and BOD; (b) the formation and precipitation of struvite ($MgNH_4PO_4 6H_2O$) which may be used as P fertilizer (Woods *et al.,* 1999); and (c) conditions that induce microbial P consumption exceeding metabolic requirement (Elliott *et al.,* 2002). Tarchitzky *et al.* (2006) reported that the average concentration of organic and mineral P in secondary TWW used for irrigation in survey plots in Israel were 6.8 and 4.2 mg l^{-1}, respectively. For irrigated crops in semiarid and arid regions, P added to soils through TWW irrigation meets and even exceeds the amount commonly applied via fertilization with freshwater, which is not only a beneficial economical characteristic for TWW use in agriculture (Fine and Hadas, 2012), but also a potential environmental pollutant. The major concerns in using TWW as a source of P are: 1. Environmental pollution hazards from P runoff and/or leaching and 2. Excess accumulation of P in the soil that may affect the availability of other nutrients.

The main processes that influence P availability and its environmental pollution hazards are the chemical reactions of the added inorganic and organic P in the soil. Two main chemical characteristics that affect P fate in soil are unique to TWW: 1. P is found in TWW as both organic and inorganic forms, which differ in their chemical and mobility properties and utilization by plants and 2. TWW includes dissolved organic molecules that might chelate P, and thus increase P mobility in soil. The organic P species in TWW have not been sufficiently identified. In activated sewage sludge ~50% of organic P was reported to be phospholipids, 30% inositol hexaphosphate (IHP) ($C_6H_6(H_2PO_4)_6$), and 20% humic compounds (Fine and Mingelgrin, 1996; Pierzynski *et al.,* 2005).

The major questions raised while irrigating with TWW are: 1. What is the fate of the organic P supplied with TWW in the soil? and 2. How do the dissolved

organic molecules affect inorganic P adsorption, precipitation and mobility in soil? Precipitation reactions of P with other minerals are slow processes reaching equilibrium in time scales of months to years (Bar-Yosef, 2011). The rate of precipitation of Ca-P minerals is considerably reduced in the presence of soluble organic matter (Inskeep and Silvertooth, 1988). Adsorption reactions are very rapid, reaching equilibrium in the time scale of seconds to days. Consequently, sorption reactions are expected to control the immediate concentration of P in the soil solution following irrigation with TWW, while further precipitation processes will modify P concentration with time (Bar-Yosef, 2011). Several studies showed a decrease in P sorption in the presence of humic acid (HA) and fulvic acid (FA), suggesting competitive adsorption. Sibanda and Young (1986) found that the effect of HA on P adsorption diminished with increasing pH, and vanished at pH ~7.6. Another mechanism through which organic compounds influences P sorption and mobility in soil is P complexation. Dissolved and stable complexes enhance P mobility in soil due to reduced P adsorption (Guppy *et al.,* 2005), whereas immobile, stable organic complexes with P increase its sorption and reduce P mobility in soil. Several studies showed that at similar P concentration and pH, adsorption of IHP-P exceeds the adsorption of inorganic P by clay minerals and metal-oxides (Celi *et al.,* 2001), probably due to the much higher charge density of IHP-P than inorganic P (Condron *et al.,* 2005).

The above shows that the chemical composition of TWW may have confounding effects on the processes that control P concentration in the soil solution. Bar-Yosef (2011) found in a soil column laboratory experiment that at similar P concentration in equilibrium solution the adsorption of IHP-P by a loess soil was approximately tenfold greater than inorganic P. However in field experiments, P was leached to deeper layers than P added as mineral fertilizer with freshwater (Sommers *et al.,* 1979; King *et al.,* 1990). For example, Lado *et al.* (2012) reported higher concentrations of available P in a non-calcareous sandy soil irrigated with TWW for 8 years than in fertigation with freshwater down to 90 cm depth (Figure 7). In a calcareous clayey soil the difference in the soil available P between the TWW and the freshwater was smaller and the depth of higher P concentration was just 60 cm.

The following mechanisms were suggested to the enhanced mobilization of P to deeper soil depths under TWW irrigation. Barton *et al.* (2005) suggested that in soils irrigated with secondary effluents the leaching depth of P was greater due to preferential flow through macropores and soil cracks. Bar-Yosef (2011) suggested an alternative mechanism to explain preferential P flow in soil is pores coating by hydrophobic material found in effluents or biosolids. The coating decreases the soil surface area available for reaction, and hence P adsorption, and the hydrophobicity is more effective in reducing water flow in micropores than in macropores. Reduced micropore flow induces greater water transport via macropores and thus water movement in soil is accelerated. The overall effect is that in TWW irrigated soils water flow is faster than in freshwater irrigated soils, P adsorption is reduced, and P leaching is enhanced.

Potassium

Raw wastewater contains high concentrations of mineral K, the range depending on the water source. The K added to raw wastewater by municipal use is in the range of 5-17 mg l^{-1} (Feigin *et al.,* 1991). Secondary and advanced treatments do not usually affect K concentration in TWW (Feigin *et al.,* 1991; Fine and Hadas, 2012). Consequently, K concentration in the TWW used for irrigation is in the range of 10 to 40 mg l^{-1} (Fine and Hadas, 2012). Unlike N and P, the inorganic K ion is the dominant form of K in TWW and therefore, the fate of K originating from TWW is not different from that of K from freshwater or K supplied by fertilizer. For irrigated crops in semiarid and arid regions, K added to soils through TWW irrigation can meet or even exceed the amount commonly applied via fertilization with freshwater. The recommended application of K for principal outdoor irrigated crops in Israel is in the range of 90-320 kg ha^{-1} (Fine and Hadas, 2012). Consequently, TWW may be considered a beneficial source of K for crops (Fine and Hadas, 2012). Tarchitzky *et al.* (2006) reported that the average concentration of K in freshwater and secondary TWW used for irrigation in survey plots in Israel was 4.5 and 26.0 mg l^{-1}, respectively. The total applied K (including fertilizers) in the freshwater and the TWW plots was 140 and 247 kg ha^{-1}, respectively. The soil (0-120 cm) extractable K by CaCl in the TWW plots was higher by 9.2 mg kg^{-1} or 14% than in the freshwater plots. Higher soluble K concentration in the upper soil layers after several years of irrigating various orchards with TWW were also reported by Lado *et al.* (2012); they reported that in a non-calcareous sandy soil the influence of TWW on soluble K concentration was down to 90 cm depth, whereas in a calcareous clayey soil the difference in the soluble K between the TWW and the freshwater was smaller and only to a depth of 30 cm. It seems that unlike P, K accumulation in soils irrigated with TWW carries no special risk and that the amount of K supplied by the TWW can be considerable and should be accounted in fertilization management of crops irrigated with TWW.

Micronutrient availability

Wastewater irrigation can affect micronutrient availability in the soil in two ways: (i) by containing them and adding them to the soil, and (ii) by contributing constituents of sewage effluent (e.g. soluble organic and inorganic ligands) that can alter soil and solution composition and processes that affect solubility, mobility, and bioavailability of elements, especially those of trace metals. The first mode is demonstrated in Table 3 that presents general quality parameters and micronutrient content in raw WW and in three secondary effluent types. Evidently, the lesser the enhanced wastewater treatment, the higher the micronutrient and macronutrient content of its effluent. The concentrations of micronutrients (Fe, Zn, Cu, Mn, Mo and B) in secondary TWW types are usually within the range needed by various crops. This is demonstrated in Table 3 by comparing element load to crop requirements (Hochmuth *et al.,* 1991, Table 6).

Nutrient solutions are usually applied at concentrations 10-25% of the full strength shown in Table 3. Because of the high oxygen demand of raw and secondary TWW types, iron is present in the soluble, reduced form Fe^{2+}, and in soluble organic complexes. Recharging the TWW into the aquifer sediments during the soil aquifer treatment

Table 3. Micronutrients concentrations in wastewater effluent types (taken from Table 1) and loads (based on 500 mm irrigation head) compared with crop requirement (Hochmuth *et al.*, 1991).

Ele-ment	Concentration				Load				Crop require-ment[1]
	Raw	OPE	MBTE	SAT	Raw	OPE	MBTE	SAT	
	(mg l^{-1})				(g ha^{-1})				(g ha^{-1})
Fe	1.96	0.25	0.31	0.037	9800	1250	1550	185	400
Zn	935	166	119	70	4675	830	595	350	170
Cu	295	34	15	6	1475	170	75	30	170
Mn	85	59	41	14	425	295	205	70	850
Mo	10	5	5	1.5	50	25	25	7.5	35
B	550	590	510	190	2750	2950	2550	950	170
Ni	62	30	21	4	310	150	105	20	

[1]Data from Hochmuth *et al.* 1991 (reviewed in 2009), Table 6.

(SAT) as an advanced tertiary purification process further reduces micronutrient concentration by adsorption and precipitation reactions (Lin *et al.*, 2008). Depending on the extent of the wastewater treatment, the overall micronutrient loads of Zn, Cu, Mn, Mo and B, at a 500 mm annual irrigation (Table 3), are as follows (g ha^{-1}, gross crops need in brackets as given by Hochmuth *et al.*, 1991): Fe: 185-1,250 (400), Zn: 350-830 (170), Cu: 30-170 (170), Mn: 70-295 (850), Mo: 7.5-25 (35), and B: 950-2,950 (170) g ha^{-1}. These loads are by far more balanced with crop needs than freshwater irrigation where micronutrients are applied (if at all) only in response to deficiency symptoms. Some elements, like boron, are in excess of the need of most crops. As mentioned earlier, the agriculture and environment authorities in Israel have managed to drastically reduce B concentrations in TWW (Table 1) by largely eliminating B from household detergents and by requiring removal of B during seawater desalination processes.

The second mode by which TWW affects micronutrient availability is by its effect on soil solution properties and characteristics that affect mineral stability and element solubility. Recent comprehensive reviews on the behavior of heavy metals in TWW irrigated soils are available (Hass *et al.*, 2011; Kunhikrishnan *et al.*, 2012).

Hass *et al.* (2011) concluded that crop irrigation with advanced municipal TWW with little or no industrial inputs and low metal and TOC contents, should bring about minor if any accumulation of metals in the soil and crops, and impose little, if any, risk for leaching of metals. This is especially true in soils with pH above 6.5 and when the irrigation is managed according to crop water requirements rather than dictated by wastewater disposal considerations.

Irrigation with TWW can also promote additional geochemical processes that further impact solubility of TWW- and soil-borne metals. Depending on TWW

quality, composition, irrigation practice and irrigation loads, TWW irrigation is likely to promote reductive dissolution of ligand in soil. With amorphous minerals and free oxides, mainly those of Mn and Fe, being more susceptible, such processes will result in release of soil-borne metals and lead, over time, to diminishing in soil affinity towards transition metals.

Conclusions

Regulations for TWW irrigation should follow a reduced risk approach; achievable either through advanced treatment of WW to meet fecal coliform (FC) limits (< 10 cfu 100 ml^{-1} for unrestricted irrigation), or by implementation of on-farm preventive measures and practices. The latter relies on consideration of a wide range of FC barriers, such as TWW quality, crop type, cropping methods, harvesting and irrigation methods, and the nature and intended use of crop.

Irrigation systems utilizing TWW and/or chemical fertigation can be impaired by fouling of pipes and equipment and of clogging of emitters. Prevention of clogging requires attention and investment and must be designed to specific water quality.

Management of water containing high concentrations of salts must consider both leaching requirements (water applied to remove salts from the root zone) and crop response to stress caused by combinations of all possible factors. Due to the need for leaching, long-term irrigation with saline water under arid conditions is problematic. Sustainable cultivation must provide for collection and disposal of the leached salts and water or, alternatively, reduce the leaching.

Irrigation with TWW offers utilization of otherwise non-exploited water and nutrient resources. Awareness of the grower regarding the need for adjusting N, P and K fertilization by taking into consideration the composition of TWW will reduce the potential for environmental pollution by N and P. The effect of the organic P component on P fate in soil is unclear and contradictory results have been obtained in laboratory and field studies. New approaches and innovative methods are required for better understanding of the processes controlling organic and inorganic P transport in soils irrigated with TWW. Management methods have to be applied to minimize nitrate leaching toward groundwater and nitrate and phosphate runoff to surface water resources.

There is little, if any, risk for accumulation of metals in the soil and crops, and for leaching of metals when crops are irrigated with advanced municipal TWW with little or no industrial inputs. This is especially true when irrigation is managed to meet crop water requirements and in soils with pH above 6.5.

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<p style="text-align:center">**Chapter 11**</p>

Conservation agriculture farming practices for optimizing water and fertilizer use efficiency in Central Asia

Mina Devkota[1], Krishna P. Devkota[2], Raj K. Gupta[3], Kenneth D. Sayre[4], Christopher Martius[5] and John P.A. Lamers[6]

Abstract

Intensive soil tillage and mismanagement of irrigation water and fertilizers under current agricultural practices have accelerated the pace of degradation of irrigated drylands in Central Asia. Increasing water scarcity and concerns of irrigation water quality have further raised serious doubts about the sustainability of current conventional agricultural systems. In the face of these environmental and economic challenges, there is a need to introduce new agricultural systems which improve the productivity of natural resources as well as of external inputs and help prevent soil degradation. Conservation agriculture (CA) practices such as reduced tillage, residue retention and proper crop rotations offer such solutions but research on CA in Central Asia is still in its infancy. This paper reviews various studies from the irrigated zones of Central Asia wherein efficiency of various CA practices under different cropping systems have been evaluated. These studies have shown that cultivating crops on relatively permanent raised beds with residue retention, potentially saves 12-23% irrigation water in wheat and maize. Compared with conventional agriculture practices, raised bed systems saved up to 70% of irrigation water in rice. Similarly, permanent raised beds and N management based on crop demand have improved nitrogen use efficiency in irrigated drylands of Central Asia.

[1] International Maize and Wheat Improvement Center (CIMMYT), Kathmandu, Nepal, m.devkota@cgiar.org
[2] International Rice Research Institute (IRRI), Manila, Philippines, k.devkota@irri.org
[3] Borlaug Institute for South Asia/CIMMYT, New Delhi, India, rajgupta@cgiar.org
[4] International Maize and Wheat Improvement Center (CIMMYT), Mexico, ken.sayre@gmail.com
[5] Center for International Forestry Research (CIFOR), Bogor, Indonesia, c.martius@cgiar.org
[6] Center for Development Research (ZEF), Bonn, Germany, j.lamers@uni-bonn.de

Introduction

Between 1950 and 1990, irrigation was extended to about 8 million ha (Mha) of the dryland ecosystems in the five Central Asian republics of Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan (FAO, 2000; Roll *et al.*, 2006). This shifted land use of drylands from mono-cropping to intensively cultivated irrigated land use. Although the area of the irrigated systems was limited to less than 3% of the total Central Asian land area of 397,000 km^2, it served as one of the largest irrigated zones worldwide. This expansion of the irrigated area during the Soviet time was instrumental in increasing irrigated cotton production (Kienzler, 2010) and providing livelihood security for 70% of the 63 million inhabitants. However, water consumption tripled in less than four decades to about 96.3 km^3, of which 90% was used for irrigating crops (Orlovsky *et al.*, 2000). Availability of irrigation water and use of heavy agricultural machinery intensified crop production but it also led to soil compaction, erosion, water logging, soil salinization and nutrient mining (Devkota, 2011a; Devkota *et al.*, 2010; Qadir *et al.*, 2009). Annual loss in crop production of the irrigated Central Asian drylands due to land degradation has been estimated at about USD 31 million (Sutton *et al.*, 2007). This endangers the livelihood security and economic prosperity of the entire region. Anxiety for ecological sustainability and future food security, especially given the predicted water scarcity in the region (Martius *et al.*, 2009), has led to research efforts examining land use practices that increase water use efficiency, save irrigation water, and make effective use of soil fertility and fertilizer amendments such as nitrogen (N), which is the most limiting nutrient in regional crop production (Kienzler, 2010).

Since agriculture will keep growing in the region, it will need to become more efficient and less polluting. But blueprint solutions ("one size fits all" recommendations) will not help the farming population which is in dire need for options. After decades of large-scale mechanization and intensive use of inputs, practices reminiscent of the Soviet era, the farming practices in Uzbekistan, for instance, are being changed. While improving, the country is still lagging behind with respect to crop diversification, crop rotation and conservation farming practices. The present mainstream thinking of plugging to rectifying individual problems within the farming system is insufficient, and also needed a better and more productive farming system which can be provided by CA practices.

Conservation agriculture

Conservation agriculture, which focuses on system perspectives, involves major changes in farm cropping operations through combinations of crop residue retention, minimum tillage and appropriate crop rotation (Lumpkin and Sayre, 2009). How these basic principles are implemented varies widely depending on local conditions. The key transformation strategies from conventional to CA practices involve a shift away from the several practices listed below (Gupta *et al.*, 2011):

• Excessive tillage and soil erosion to no till/or drastically reduced tillage.

- Residue burning or incorporation to surface retention of residues.
- Free-wheeling of farm machinery to controlled traffic.
- Crop-based management to cropping system-based management.
- Single or sole crops to intercropping/relay cropping (rotations).
- Uneven fields to precision laser and land leveling in gravity irrigated systems.

Presently, CA practices have been adopted by farmers on more than 100 Mha worldwide (Derpsch and Friedrich, 2009). With the adoption of various types of reduced tillage practices (e.g. minimum tillage, zero-till flat, permanent raised beds), farmers can save labor and money (Gupta *et al.*, 2009; Tursunov, 2009). In addition to economic benefits, minimum tillage practices effectively minimize soil disturbance, control evaporation loss from soils, minimize soil erosion losses, enhance soil carbon sequestration, and increase water infiltration and the amount of plant-available soil water (Lal *et al.*, 2007; Wiatrak *et al.*, 2005). Controlled or reduced traffic, an important practice for the success of CA systems, is facilitated by permanent raised beds. This restricts traffic in the field to a minimum and allows following tracks already used before, thereby avoiding widespread field compaction. The rooting zone thus receives much less compaction under CA, resulting in better soil structure and higher yields compared to the free-wheeling of farm machinery. Importantly, controlled traffic also leads to fuel savings since traction is more efficient when tires run on compacted tracks (RWC-CIMMYT, 2003).

Crop residue can be a renewable source of soil organic matter. It has the potential to improve the physical, chemical and biological soil properties (Ding *et al.*, 2002), reduce evaporative water loss, and increase the water retention capacity of soils (Gant *et al.*, 1992). Crop rotations which include legume crops in cereal systems or certain cereal crops in cotton mono-cropping systems have the following benefits (Kassam and Friedrich, 2009):

- Reduces the pest populations through disruption of the pest life-cycle.
- Increases biological N-fixation.
- Helps prolonged slow-release of nutrients from complex organic molecules.
- Soil improvements by increased carbon inputs at depth, and
- Helps redistribute soil nutrients from lower soil depths to the root zone.

These practices can reduce external costs for fertilizer and chemical inputs.

The combined effect of these advantages of CA offers great potential to increase availability of water (Devkota, 2011b; Fischer *et al.*, 2002; Unger *et al.*, 1991; Wang *et al.*, 2011) and nutrients to the crop (Verhulst *et al.*, 2011) in both rain-fed and irrigated areas. Therefore, we also expect these benefits under irrigated crop production in Central Asia (Egamberdiev, 2007; Pulatov *et al.*, 2011; Tursunov, 2009).

In this review, research results on CA practices have been compiled and analyzed for the three dominant crop rotations in irrigated dryland areas in Central Asia based on data from Khorezm, Uzbekistan; i.e. (1) cotton-wheat-third crop (e.g. maize), (2) cotton-winter cover crop-cotton, and (3) rice-wheat. This paper centers on the

concurrent improvement of water and N use efficiencies, with permanent bed (PB) and zero tillage (ZT) as reduced-tillage treatments.

Laser-guided land leveling

In the lowlands of Uzbekistan average annual rainfall is generally well below 100 mm and irrigated agriculture is the only option for crop production. Irrigation water is commonly applied as basin (for winter wheat and rice cultivation) and row/furrow irrigation (for cotton cultivation). The application efficiency of irrigation water is generally low (Tischbein *et al.*, 2012), partly owing to the unequal micro-relief of the fields. Land leveling used to be commonly practiced in Uzbekistan during the Soviet era, but nowadays the majority of the commercially oriented and household farms, despite being aware of the negative impact, rarely follow this practice due to lack of funds, appropriate equipment and expertise (Egamberdiev *et al.*, 2008).

At present, more than 90% of the irrigated croplands in Uzbekistan suffer from high groundwater table and varying levels of secondary salinization (Ibrakhimov *et al.*, 2007) due to high percolation losses from canals and water courses and excess water application in uneven fields. The most commonly implemented land-leveling technique is a tractor-drawn leveler equipped with a blade or a wooden bar used for moving soil from higher to lower elevations. While this provides a certain degree of leveling, irrigation exposes continued, strong small-scale topographic variations that prevent even water distribution on the field, and differences in soil salinization across the field are emphasized. This kind of leveling needs to be repeated frequently, adding to costs. Unleveled fields show an uneven pattern of crop growth and development, have higher weed populations, and display uneven crop maturation rates –all factors that lead to yield losses (Egamberdiev *et al.*, 2008).

Laser-guided land leveling is an efficient option for precise leveling. Laser leveling provides the same benefits to CA as to conventional agriculture under surface irrigation conditions. Laser-guided land-leveling benefits crop cultivation as it results in improved water distribution, negligible water losses and a high irrigation water application efficiency as shown by Abdullaev *et al.*(2007): average cotton yield was increased by 26%, and crop water productivity by 32% in the laser-leveled field compared to the conventionally leveled fields. Follow-up studies showed that the initial costs of laser-guided land leveling exceeded those of conventional leveling procedures, but this was compensated for by gains in productivity and water conservation. Water demands were reduced by 25%, and crop germination, establishment, growth, and stand uniformity lead to increased crop yield by 24%, whilst weed infestation was reduced by up to 40% (Egamberdiev *et al.*, 2008; Jat *et al.*, 2011; Rickman, 2002). Furthermore, once the field is laser-leveled, the investment pays off for a longer period under CA where no further soil tillage is applied that could destroy the leveled surface. Groups of farmers could share the costs of purchasing laser-leveling equipment, and service providers could level fields as paid services to maximize the use of specialized equipment.

Further, laser leveling can minimize the yield reduction during transformation from conventional to CA practices. This has been illustrated by research findings in Khorezm region, Uzbekistan, where the cotton yields were not significantly different between

conventional and CA practices in both cotton-cover crop-cotton and cotton-wheat-maize rotation systems (Devkota, 2011b; Lamers *et al.*, 2009). Overall, research findings illustrated that laser-leveling before starting CA practices can avoid yield declines during the transition period from conventional to CA (Tursunov, 2009), in addition to significant savings in irrigation water.

Water application and productivity

The above-mentioned forecasts of increasing water scarcity in the irrigated zones of Central Asia emphasize that options need to be developed that increase water use efficiency, reduce irrigation water demands and increase yields. Abdullaev and Molden (2004) have reported that water productivity of irrigated agriculture in Central Asia has drastically decreased in the last few decades. The average water productivity of the entire cotton-growing area in the Syr Darya basin, dominated by flood and furrow irrigation practices, is about 0.37 kg m^{-3}, considerably lower than the world average of 0.60 kg m^{-3} (Abdullaev and Molden, 2004). Permanent raised bed (PB) planting systems facilitate irrigation through furrows and are therefore considered a technology that saves irrigation water and reduces soil erosion (Hassan *et al.*, 2005; Sayre and Hobbs, 2004). Kalashnikov (2009) found reductions of 22-32% in irrigation water demand, while crop yields improved by 24-32% with PB systems compared to the conventional flat planting in wheat production in southern Kazakhstan. In Khorezm, Uzbekistan, Devkota (2011a; 2011b) reported that wheat and maize grown on PB saved 12-23% irrigation water, and improved crop water productivity by 27-83% compared to conventional practices in both cotton-wheat-maize and rice-wheat rotation systems (Table 1). Likewise, the water saving in rice was 70% in PB system, and crop water productivity was twice that of the conventional practices. Such reductions in irrigation water usage were confirmed earlier (Jat *et al.*, 2009; Jat *et al.*, 2011; Kalashnikov *et al.*, 2009) and are expected to have considerable importance for Central Asia with decreasing water supply and increasing demands for irrigation water.

Furthermore, retention of crop residues in the PB system also increases water use efficiency. Ibragimov *et al.* (2011) reported that the retention of all residues of the previous crop improved both crop water and irrigation water use efficiencies during 4 years, except for cotton cultivation in one season. Irrigation water use efficiency for cotton lint increased from 0.41 kg m^{-3} at the onset to 0.59 kg m^{-3} at the end of an experiment when PB was combined with full crop residue retention. Similarly, soil moisture was higher (3-6%) under PB with crop residue retention than under residue removal (Devkota, 2011b). Thus, PB with residue retention can have greater importance in arid regions of Central Asia, as the practice can save irrigation water and increase crop water productivity (Table 1).

Table 1. Irrigation water application and crop water productivity of crops grown under cotton-wheat-maize and rice-wheat rotation systems in Khorezm Region, Uzbekistan, 2008-2010.

Crop	Water application (m³ ha⁻¹)		Crop water productivity (kg m⁻³)	
	Permanent raised bed	Conventional system	Permanent raised bed	Conventional system
Cotton-wheat-maize system				
Cotton	4,450	4,450	0.88	0.88
Wheat	4,770	5,380	1.73	1.36
Maize	6,285	8,150	0.88	0.48
Rice-wheat system				
Rice	17,250	63,000	0.27	0.11
Wheat	5,225	6,475	1.48	1.14

Nitrogen management with CA practices

Nitrogen (N) is one of the most important nutrients for crop production and is a highly limiting nutrient under irrigated crop production in Central Asia (Ibragimov, 2007). Due to reduced soil tillage and residue retention under CA, N dynamics can vary considerably compared to conventional systems (Anga´s *et al.*, 2006; Limon-Ortega *et al.*, 2000). It is not easy to place top dressed N fertilizer deeply in the soil in the presence of unincorporated surface residues. Carter and Rennie (1984) have reported that, due to high C/N ratio of many crop residues, there is an immobilization of applied fertilizer N in the crop residues and generally lower crop N-use efficiency during the initial stages of CA. Hence, higher N applications than with conventional practices without residue retention are recommended to counterbalance this initial N immobilization (Hutchinson *et al.*, 1995). Similarly, Hickmann (2006) and Sommer *et al.* (2007) postulated that crop residue retention should be combined with additional N applications to counterbalance N immobilization during the conversion from conventional to CA practices. However, in the long run, lower N losses and greater retention of fertilizer N due to immobilization can improve crop N use efficiency by subsequent re-mineralization of the N in better synchrony with crop needs (Karlen, 1990). In order to avoid immobilization of top-dressed fertilizer N by surface residues, new practices such as deep placement of 80% of the total N between rows at seeding, and use of the Turbo Happy Seeder machine which cuts and manages the standing stubble and loose straw in front of the furrow openers and retains it as surface mulch, has been found effective (Sidhu *et al.*, 2007). Recently Singh *et al.* (2011) have reported that a single basal dose of N (80% of the recommended N) proved as effective as split doses of fertilizer N applied to irrigated wheat crop in the Indian Punjab. Top-dressed N at anthesis, on the other hand, improved grain protein content and had little effect on yield. More recent findings from Uzbekistan have shown that during the transition period from conventional and CA practices in irrigated crops the need for N did not differ (Devkota 2011b; Figure 1, Cotton). Furthermore, after
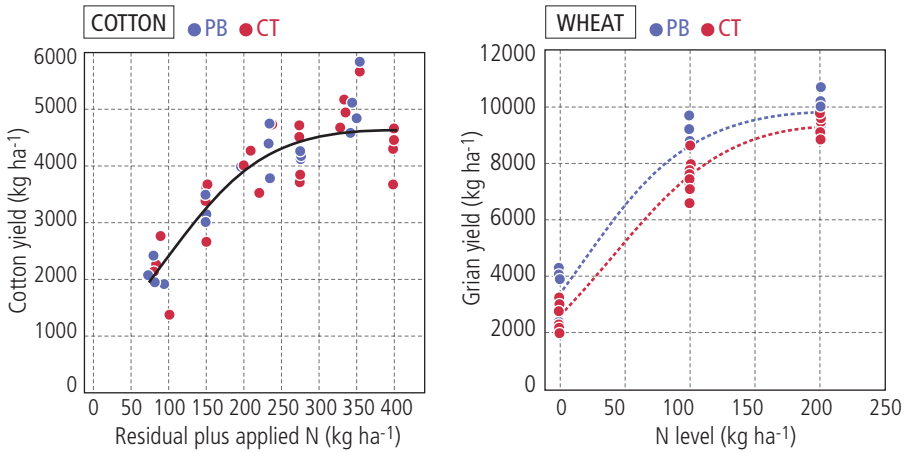
Figure 1. Response of cotton and wheat grain yield under different N levels in conventional tillage (CT) and permanently raised beds (PB) in Khorezm region, Uzbekistan. (Source: Devkota, 2011b)

one season of CA practices, crops grown on PB showed a higher response to applied N under both low and high N application rates than in the conventional systems, with a 6-14% higher grain yield of wheat in PB under the same N levels as in conventional practices (Figure 1, Wheat). Similarly, in an experiment conducted in Northwest Mexico, Limon-Ortega *et al.* (2000) reported that changing the tillage method from CT to PB increased grain yield of wheat at both low and high N application rates in a maize-wheat rotation system. In Uzbekistan, after one season of CA practices, both agronomic and apparent N recovery efficiencies were higher in wheat and maize grown under PB than in CT systems (Table 2). This was due to better initial growth and constantly higher soil moisture availability in PB, which increased N availability and increased crop N uptake (Devkota, 2011b). We therefore conclude that, for both cotton-wheat-maize and cotton-cover crop-cotton rotation systems, crops can be grown in PB with the same N dose as in CT systems without reduction in crop yield.

The retention of crop residues in PB systems increased crop yields without N application, while with N application residues did not have any effect until the second cropping cycle. Grain yields were slightly higher in the third cropping cycle with CA practices (Devkota, 2011b). This suggests that in a high-production environment (i.e. under high N application) such as the irrigated drylands of Central Asia, the benefits of crop residues accrue over time.

Although residue retention has beneficial effects both in low- and high-yielding environments, retaining all residues from all crops in the rotation is unnecessary. This is especially true in wheat-based systems under irrigated conditions where substantial amounts of crop residues (8-9 t ha^{-1}) are produced (Devkota, 2011b). In fact, leaving these levels of residues as a thick surface layer reduced seedling emergence and hindered field operations such as of seeding, irrigation, and fertilizer management. Likewise, in

Table 2. Agronomic nitrogen (N) use efficiency (kg grain per kg N applied) and apparent N recovery efficiency (%) of N fertilizer applied in wheat and maize under permanently raised beds and conventional tillage method in Khorezm, Uzbekistan.

Tillage	Wheat		Maize	
	Agronomic N use efficiency (kg kg^{-1})	Apparent N recovery efficiency (%)	Agronomic N use efficiency (kg kg^{-1})	Apparent N recovery efficiency (%)
Permanent raised bed	43	120	28	80
Conventional tillage	42	107	16	44

a 6-year study of CA, Salinas-Garcia *et al.* (2001) reported that under the conditions of rapid oxidation of soil organic matter, it is necessary to leave a maximum of 4.0 t ha^{-1} of crop residues. In the degraded croplands in Uzbekistan after two seasons of CA practices, partial removal of the residues from the fields helped achieve a balanced use of residues, with some of the residues used for other purposes such as stock feed, thus integrating better with other locally important agronomic and economic demands without compromising crop yield.

The introduction of winter cover-crops in the rotation reduced N leaching and did not result in groundwater pollution (Staver and Brinsfield, 1998; Touchton *et al.*, 1995). This was confirmed by Devkota (2011b) for the irrigated drylands in Central Asia where the introduction of a winter cover-crop into a cotton mono-cropping system reduced the leaching loss of N to the groundwater by one-third, and increased N use efficiency. This was mainly due to the uptake of soil mineral N by the cover crop, which reduced N loss during early-spring salt leaching.

In a 2-year study on the rice-wheat systems in Uzbekistan, Devkota *et al. (2013a)* found the greater losses of mineral N with full retention of crop residues than with complete residue removal. This occurred in both PB and zero-till (ZT) flat planting, but only during the rice cropping cycles, where about 6-7 t ha^{-1} of wheat residues were retained. The higher N loss was a result of a sequence of events that started with the shading effect of the standing residues which slowed down initial rice growth and total plant N uptake, denitrification and leaching loss due to frequent alternate wet and dry irrigation, and immobilization N in the crop residues. This effect underlines the importance of a research component in CA practices in the irrigated areas on the proper amount and method of residue management, amount and method of irrigation, and dose and method of N fertilizer management which is crucial to optimize N use efficiency in rice. Since the following winter wheat crop was not affected by the standing rice residues, N losses were not observed in wheat on either permanent raised beds or ZT flat planting. All these results indicate that residue management in rice-wheat system is crucial under CA practices.

Crop demand-based N management

The judicious use of inorganic fertilizers is essential for crop production owing to the low soil fertility in Central Asia and little use of organic amendments (Kienzler, 2010). Fertilizer application rates in excess of plant and crop requirements result in unnecessary costs to farmers and potential harm to land and water resources. This is true in particular for N use which is the most limiting nutrient in irrigated crop production (Kienzler, 2010). Under the present N fertilizer practices in Uzbekistan, grain quality of wheat remained poor, but with improved fertilizer application, for example with late applications of N at anthesis/heading, protein content in the kernel increases, and hence grain quality standards of winter wheat can be met (Kienzler, 2010).

Present crop and soil N balances are often low because N is lost through leaching (Ibragimov *et al.*, 2011; Kienzler *et al.*, 2011) and volatilization (Scheer *et al.*, 2008). Both field observations and calculations by simulation models conducted in Khorezm Region of Uzbekistan have shown that cotton N demand in the irrigated areas of Uzbekistan is in the order of 200 kg N ha^{-1} for maximum yield (Devkota, 2011b; Kienzler, 2010). However, in a study conducted in the same region for two years Devkota *et al.* (2013b) reported that the optimum cotton yields can be achieved also at N-fertilizer rates of about 150 kg N ha^{-1}. During the cotton-growing season, i.e., May-September, groundwater level in Khorezm Region becomes shallow and reaches to about a meter depth and with a 4-12 ppm nitrate concentration (Devkota *et al.*, 2013b). In a study conducted in the same region, Forkutsa *et al.* (2009) have reported that the cotton crop meets between 283 and 335 mm of its crop water demand from groundwater. It appears that the N requirement of the cotton crop could have been met through N uptake from supplemental N inputs and from the groundwater and irrigation water. Farmers are well aware of the fact that higher N applications delay the opening of cotton bolls and increase the probability that producers do not gain the highest prices which typically occur at the onset of the 4-6 week cotton harvest in Central Asia. Thus, although N leached into the groundwater can contribute to satisfying crop N demand (Kienzler *et al.*, 2011), as it ranged between 5 and 61 kg N ha^{-1}, reliance of all producers on this potential N source cannot be considered to be sustainable, since continuously lowering fertilizer N applications will gradually mine soil and water N reservoirs. Research findings showed furthermore (Djumaniyazova *et al.*, 2010) that the economically and ecologically effective N-fertilizer dose for crops in the Khorezm Region is site-specific. Relying collectively on groundwater as a source of N to cotton is not a good option. A better strategy is to adapt application methods that prevent or significantly reduce N leaching losses and increase fertilizer N use efficiency. One such common practice in Central Asia is to leave the fields fallow and practice pre-winter season heavy leaching to move down the buildup of soil salinity before the crop seeding. It is observed that NO_3-N in the groundwater is highest during early spring leaching (Devkota *et al.*, 2013b). However, more recently Devkota *et al.* (2013b) has reported that the introduction of wheat as a winter cover crop in a cotton mono-crop can capture the free mineral N and hence reduce N leaching to the groundwater.

Scheer *et al.* (2008) have reported extremely high N emission rates from cotton, wheat and rice crops, ranging from 24±9 to 175±65 kg N ha^{-1} season^{-1}. Nitrogen

emission peaks occurred immediately after N-fertilizer applications and irrigation. This suggests that a targeted timing of the N fertilizer application in accordance with plant needs could reduce N loss through gaseous emissions, and increase N use efficiency. Hence since the lion's share of nitrous oxide (N_2O) emissions occurs when irrigation and N-fertilizer are applied simultaneously under high soil temperatures (which is usually the case throughout the entire crop season in the drylands of Central Asia), N-fertilizers are best applied as subsurface placement of fertilizers or broadcast and deep seated with a pre-sowing irrigation, or applied with drip irrigation. All these options bear the potential to reduce N_2O emissions. Furthermore, a judicious choice of crop rotations while considering leguminous crops and managing crop residues would enhance soil carbon sequestration and reduce the N_2O emissions from mineral fertilizers. Such practices, however, are not widespread yet. In any case, initial research findings evidenced a high potential to increase N use efficiencies when matching crop N demand and supply.

Matching crop N demand and supply

Under the agro-ecological conditions prevailing in the Khorezm Region and in many irrigated drylands in Central Asia, knowledge of the amounts and variations in the sources of N supply during the growing season is crucial. This knowledge will determine the optimal timing and amount of fertilizer N applications. Since N supply under irrigated conditions is spatiotemporal highly variable, improved methods are required to match N applications and crop requirements. Whilst N demand in Uzbekistan is presently diagnosed by plant tissue and soil tests, these methods necessitate sophisticated laboratory equipment, funding, and time. Owing to soil and tissue sampling, transport and processing, delays are inherent which, in turn, deprives farmers of timely information to satisfy in-season plant-N demand. The application of easy-to-use and non-destructive tools for real-time N monitoring has been employed in Europe, India and the USA. The use of optical devices, such as the SPAD-502 chlorophyll meter and the GreenSeeker NDVI sensor for in-season N management has improved fertilizer N use efficiency and reduced losses of N from the soil-plant system by synchronizing N applications with crop demand and irrigation cycles (Singh *et al.*, 2011). In addition, such devices offer the advantage of making spatially variable N recommendations within a field. The combined use of CA practices and crop-demand-based N application can be the sustainable and economical options for crop cultivation in irrigated drylands of Central Asia (Egamberdiev *et al.*, 2008).

Conclusions

The relatively few studies on CA practices in the irrigated drylands of Central Asia all reported that CA practices are superior to conventional production systems in terms of crop production, and nitrogen and water use efficiency. Two consistent pieces of information similar or increases in yield and more financial benefits merit the promotion of CA on a large scale in the irrigated drylands of Central Asia. Furthermore, use of

laser-guided land leveling when combined with permanent raised-bed planting or zero-tillage and residue retention practices help improve productivity and efficiency of use of irrigation water and externally added fertilizer nutrient inputs.

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