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 Agriculture makes use of 70% of all water withdrawn from aquifers, streams and lakes.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.harmendeep78@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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