Chapter 8

Challenges of increasing water and nutrient efficiency in irrigated agriculture

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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.

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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

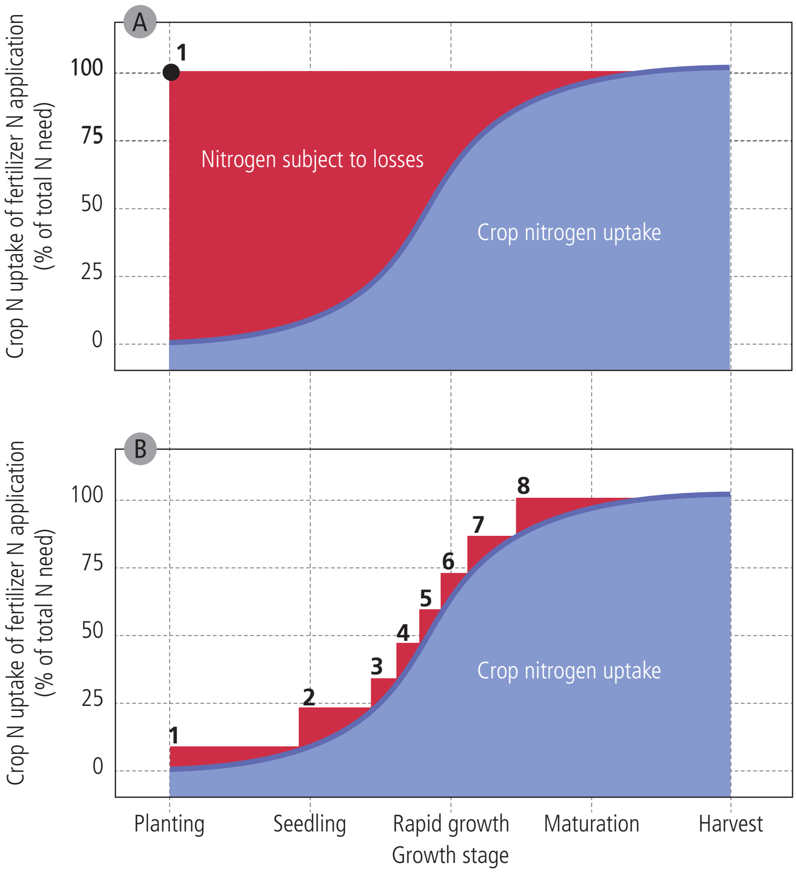

Figure 1. Example of potential N loss occurring when fertilizer is applied in a single application (A) or in eight fertigated applications (B). Inorganic N present in the soil in excess of plant demand is at risk for leaching and denitrification loss. Split applications of fertilizer will reduce the 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 $\mathrm{l\,hr^{-1}}$) 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.

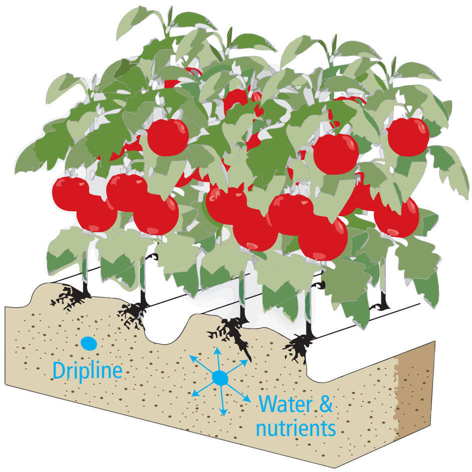

Figure 2. The use of subsurface drip irrigation delivers water and nutrients directly into the root zone. With careful management, this technique can result in enhanced resource efficiency, improved crop yields, and better harvest quality.

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

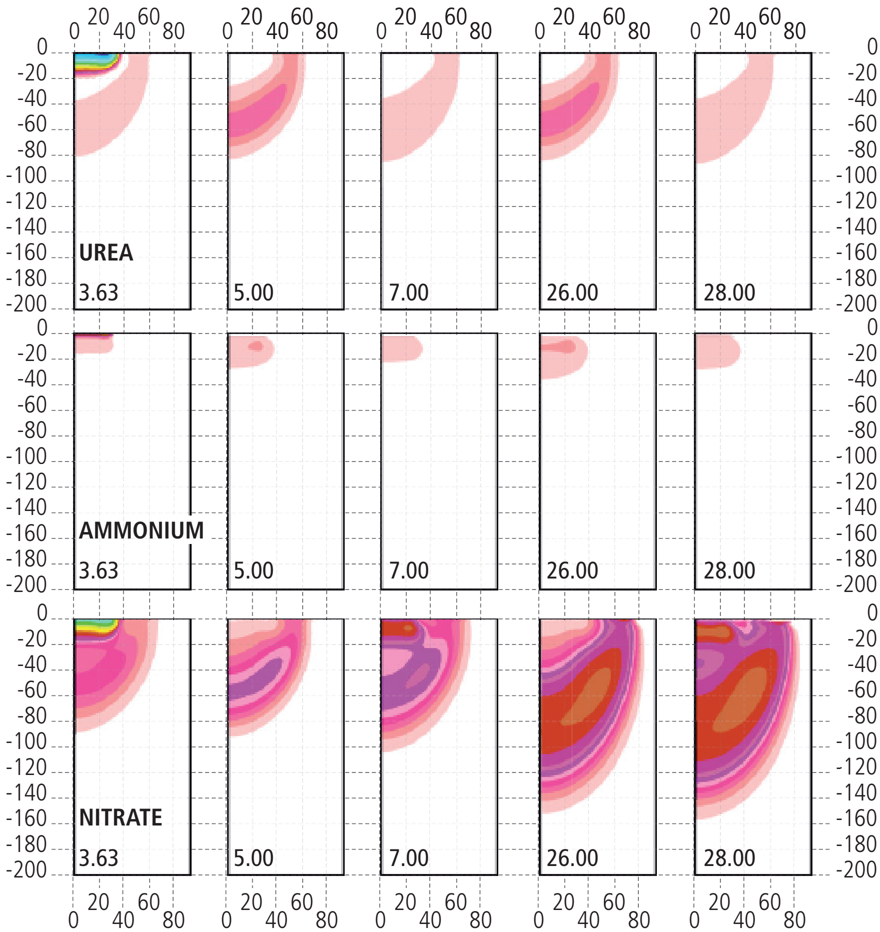

Figure 3. The spatial distribution (cm) of urea, ammonium, and nitrate fertilizer in the soil with time (up to 28 hours) following application from a drip emitter (upper left corner) (adapted from Hanson *et al.*, 2006a).

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

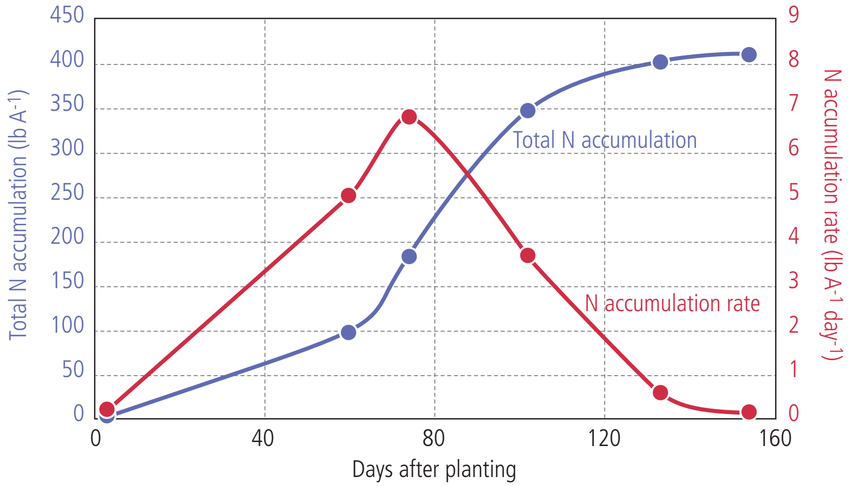

Figure 4. The rate and total accumulation of nitrogen by irrigated potato (Horneck and Rosen, 2008). Knowing that nitrogen accumulation peaks at 70 to 80 days after planting in this environment serves as a guide for fertigation practices.

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.

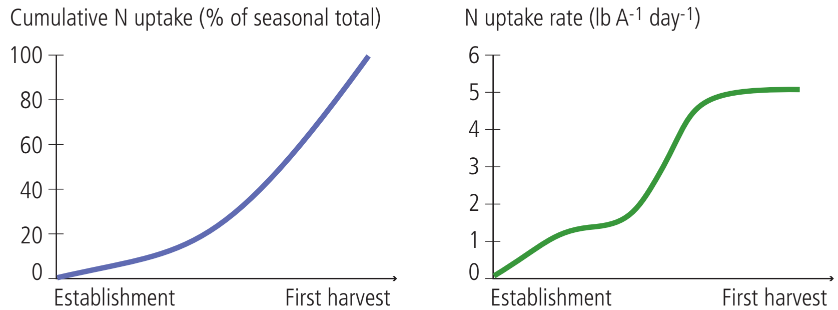

Figure 5. The seasonal pattern of nitrogen uptake (cumulative and daily) by cool-season vegetables in California (adapted from Pettygrove *et al.*, 2003).

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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