IFA AGRICULTURE CONFERENCE

Optimizing Resource Use Efficiency
for Sustainable Intensification of Agriculture

Kunming, China
27 February – 2 March 2006

IMPROVING WATER USE EFFICIENCY
IN AGRICULTURE

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Optimizing Resource Use Efficiency for Sustainable Intensification of Agriculture

"Improving Water Use Efficiency in Agriculture"

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Introduction

Improving yield per unit water has been the goal of irrigators since they first realized the supply of water was finite. When this realization first occurred in the 8-millennia history of irrigation in the great river valleys of the world (Nile, Tigris-Euphrates, Huanghe [Yellow], and Indus – Hoffman et al. 1990) is of course not known. However, by the beginning of recorded history, we can conclude attention was already focused on increasing yield. In cases where water was scarce or much effort was required to obtain water, we can also assume the water use was implicitly constrained. The irrigator may not have intended it, but these simultaneous goals increase yield obtained per unit of water used. Viets (1962) named this ratio water use efficiency (WUE).

Unfortunately, that choice of names may cause confusion. First, it is a biological response ratio and not an efficiency. Second, there are actual irrigation water use efficiencies with maximum values of 100%, pertaining to the efficiency of conveyance to the field or delivery onto the crop (Heermann et al. 1990). Finally, the shape of the response curve for a given weather, soil, and fertility level, usually termed the irrigation production function (Hexem and Heady 1978), is usually a concave-down quadratic function or a rectangular hyperbola. This means that WUE, which is mathematically represented by the average slope from zero yield to the yield obtained, has its maximum value near the origin, at low water use. So, improving WUE cannot be taken as maximizing it in the general case. On the other hand, if the amount of water is fixed, maximizing WUE is a legitimate objective, because the approach then is to maximize yield.

Another source of confusion regarding WUE is the definition of water use. In arid areas, irrigation water added could sometimes be assumed to represent the entire water use by the crop. A more general definition, which extends applicability to areas with appreciable rain, is the total water use, meaning irrigation plus effective rainfall plus extraction of stored soil water during the season. Some researchers further include drainage, and separate evapotranspiration (ET) into the evaporation (E) and plant transpiration (T) components. For the purposes of this report, we consider the definition of WUE to be the yield of interest divided by the sum of irrigation, rainfall less runoff, and decrease in soil profile water. This is also applicable to the rainfed case (irrigation = 0), which is seen below to be critical. This ratio can be stated as mass of yield per mass of water on the same area (dimensionless); however, this approach is not very intuitive. Therefore, it is more often stated as mass per unit area per depth equivalent of water (i.e., kg/ha/mm).

Increasing competition for water and increasing public concern about water quality force irrigation managers to consider two additional aspects. Those concerned with water supply usually treat irrigation as a consumptive use, meaning it is withdrawn from the supply and lost through ET. This differs from water use by hydroelectric power, for instance, which returns most water used directly to the supply. Because of this, some consider irrigation water use a direct component of the virtual water content of the grain produced. While such analyses have not been adopted universally, they are becoming more widely discussed worldwide. Those concerned with water quality focus on the indirect hydrologic returns of irrigation water via baseflow, leaching of nutrients along with the baseflow, and the direct return of irrigation tailwater with nutrients and sediment. For downstream users, degraded water often cannot be used without treatment, and thus constitutes a decrease in both water quality and quantity. In Europe and especially the USA, increasing use of commercial fertilizers in the latter half of the 1900's has contributed to degraded water quality downstream from both irrigated and rainfed agriculture. Both water supply and water quality issues present a dramatically altered context in which irrigation is now practiced.

Discussions of WUE usually relate to irrigation water use, primarily because some water supply is being redirected into consumptive use. However, considering water use efficiency in the case of rainfed culture is useful because most watershed contexts include both irrigated and rainfed (non-irrigated) areas. From the most-general perspective, managing water in the rainfed case means improving water use efficiency under conditions of much more limited and erratic water supply. Finally, in many areas of the world, problems of excess water significantly reduce yield and contribute to water quality issues in both beneficial (dilution) and non-beneficial (contaminant transport) ways.

Historical attempts to reduce water use first focused on reducing direct losses. These include reducing loss in distribution (leaks) and reducing loss in delivery (lower pressures, larger droplets, less evaporation). During the 1960's and 1970's, emphasis was placed on improving timing of delivery (irrigation scheduling), which was intended to both reduce possible excess water use and optimize yield (Martin et al. 1990). Following this general trend was the development of surface drip irrigation, or microirrigation, usually for high-value crops (Bucks 1995). For lower maintenance and reduction of E, microirrigation systems were placed below the ground surface (subsurface drip irrigation or SDI) (Camp 1998; Camp et al. 2000). The precise timing of irrigation scheduling as mentioned above was combined with addressing soil spatial variation into what is now known as precision irrigation (Camp et al. 2002; Sadler and Camp 2002).

Almost all aspects of crop culture have been adjusted to improve yield: irrigation (as mentioned above), fertilization, row spacing and orientation, plant population, seed depth, tillage, residue management, and timing of growth during the year. Other approaches include crop selection, double cropping, and intercropping to use water when the supply is most likely available. Plant breeding has improved drought tolerance. Efforts to reduce T via stomatal regulation appear to result in too much lost yield, and the authors are not aware of much success in this regard despite significant focus on the topic. Additional approaches to improving water use efficiency are in Howell et al. (1990) and Heermann et al. (1990).

Historically, manures and organic materials were used as fertilizer. Commercial inorganic fertilizers became prominent about 1950. For a given water supply, such as a fixed irrigation amount or in the rainfed case, fertilizing generally raises WUE. [An exception in the water-limited case is when vegetative growth early in the season exhausts the water supply before grain filling, in which case yield may be no more than in slower-growing areas that use water later in the season (Sadler et al. 2000a,b).] In some cases, nutrient supply may be the key limiting factor; in these cases, yield response to fertilizing may be substantial. However, even if that is not the case, growth often increases more than ET because ET is governed more by the energy balance than is growth.

Determining crop responses to nutrient and irrigation inputs has often been done independently. Nutrient response tests were designed to be either well-watered or rainfed, and irrigation production functions were determined according to fertility recommendations for the well-watered case. This is consistent with the economic conditions of the time. With very low-cost inputs, response curves were assumed to plateau at a maximum yield for both water and fertilizer (usually nitrogen, N), with explicit negligence of the economics (Stanford and Legg 1984). However, fertilizing until there is no additional response invites the violation of assumptions, namely, that the soil profile neither gains nor loses the input in any way except crop uptake. Losses by leaching and transformation to gaseous forms in effect shift the response curve toward higher inputs. Finally, failure to set realistic yield goals, often used as the basis for fertilizer amounts, has resulted in rates significantly higher than needed. If yield goals are the sole basis for fertilizer rates, failure to account for other sources of the nutrient also invites overfertilization. While the same considerations apply to irrigation amounts, in practice, the water balance is more straightforward to explain and perhaps better understood than corresponding balances for nutrients.

More recent analyses of fertilization rates explicitly seek the economic optimum (e.g., Sawyer and Randall 2005), as do those for irrigation amounts (Mjelde et al. 1990). However, little data is available regarding the dual-input optimum. Even discussions of fertigation, or injecting fertilizer directly into the irrigation water, focus on comparisons to conventional fertilizer application (Threadgill et al. 1990). In discussing future research needs, they allude to the need for thorough investigation of nutrient concentrations and rates of crop uptake, but do not explicitly state a need for optimizing for both irrigation amount and fertilization simultaneously.

A limited number of individual irrigation/fertigation experiments have sought the combined optimum. For one location where research equipment made the requisite experiment possible, Camp et al. (2002) provided spatial variation in the marginal benefit to N fertilizer for well-watered maize on both a relatively uniform soil and on a highly variable soil. In both cases, variability in the patterns were such that in-season detection of N need would be required to attempt to optimize both irrigation and N. Using data from one of those experiments, Lu et al. (2004) provided response surfaces for the combined optimum for irrigation water and N fertilization for yield-maximizing and profit-maximizing strategies.

Case Studies

As illustrated below, focusing solely on increasing WUE with fertilization can have long-term deleterious consequences. We present four case studies illustrating approaches for improving water and nitrogen use efficiency. Three affect the Gulf of Mexico hypoxia issue and are currently of quite high priority in the USA. The Platte River case illustrates the water quality condition of an alluvial aquifer as a result of 5 decades of intensive fertilized maize production, and the steps taken to remedy it. The US Corn Belt case shows the links between water management and water quality in a tile-drained, primarily rainfed, intensive production system, and proposed steps to address them. The Lower Mississippi River Valley case describes a water-conserving rice production system where the drainage-water quality risk may also exist. Site-specific irrigation results from the US Southeast Atlantic Coastal Plain illustrate some of the only site-specific water and nitrogen production functions in the world.

Platte River Case Study

The Platte River system in NE Colorado and Nebraska provides a water supply to an extensive irrigated area within and near its alluvial plain. It has been known for some time that the combination of irrigation and fertilization on sandy soils pose a potential for nitrate loss into the shallow alluvial aquifer (Smika et al. 1977; see figure 1 for fluxes). Increasing use of commercial fertilizers, particularly N, and intensive production of maize are noted as contributing to the gradual buildup of nitrate in the groundwater (Ferguson et al. 1991). In the central Platte Valley, irrigation water contained an average of 19 mg/L nitrate-N during 1988 (Central Platte Natural Resource District, 2006). To address the issues of groundwater contamination by fertilizer N, research and extension efforts have been conducted in both the South Platte River Valley of Colorado and the Central Platte River Valley in Nebraska. One Colorado project emphasized fertilizer type (anhydrous ammonia, urea-ammonium nitrate, and ammonium nitrate) and timing (conventional pre-plant, at planting, and sidedress applications vs. fertigation 7-10 times during the season; Smika et al. 1977; Duke et al. 1978). The combinations tested resulted in 12 to 73 mm of deep percolation and 19 to 60 kg/ha of nitrate-N loss for fields that had been in production since the mid-1960's. While deep percolation in these studies carried an average of roughly 10 kg/ha of nitrate-N per cm of percolation, Duke (1986) pointed out that winter precipitation cannot be neglected. He proposed that late-season irrigations be reduced to provide storage capacity in the soil and reduce wintertime percolation losses.

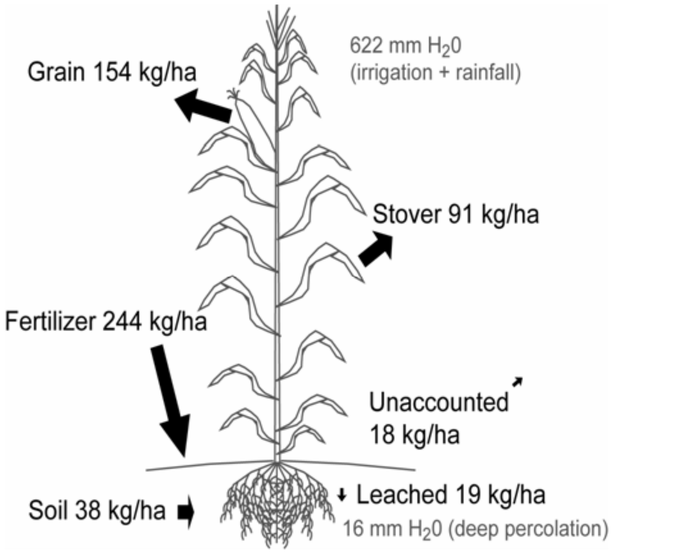

Figure1. N balance for an irrigated maize crop using good water management. Root zone was considered as 1.2 m for the particular soil (data from Smika et al., 1977).

Also in Colorado, Bausch and Delgado (2005) showed that N fertigation according to in-season assessment of plant N status using green and near-infrared reflectance could significantly reduce fertilizer applied in some cases, while maintaining or slightly increasing yields.

In the Central Platte River Valley of Nebraska, a 21-year effort to improve irrigation and fertilizer management also includes research and extension efforts. The Platte Valley Nitrogen and Irrigation Management Demonstration Project encourages credits for soil-supplied N through mineralization and also credits for N contained in the irrigation water. It also encourages producers to set realistic yield goals. During this project, participating producers achieved 97% of their yield goals. They credited 75 kg/ha of N for soil mineralization and 31 kg/ha for irrigation water N, on average. Concurrent with voluntary management, some of these areas also used regulatory policies to improve groundwater quality. The Central Platte Natural Resources District Groundwater Management Area (GWMA) was established in 1988. A four-tiered approach depends on the severity of the local groundwater quality problem. In Phase I, for areas < 7.5 mg/L nitrate-N, the only constraints are to prohibit fall- and winter-applied fertilizer on sandy soils and delay application on other soils until November 1. In Phase II, for areas between 7.6 and 15 mg/L, fertilizer application is prohibited until March 1 and extensive monitoring of water and nutrients is required. Phase III, for areas > 15 mg/L, includes all the prior requirements, plus some method to spread the availability of N, which can be a split application, nitrification inhibitors, or a sidedress application. Phase IV, which is enabled by legislation but has yet to be implemented, would include all areas where groundwater nitrate levels are not declining at an acceptable rate, and District officials would be actively involved in setting yield goals and fertilizer application rates. While it is not possible to isolate which of the voluntary or regulatory approaches has achieved the success, the groundwater nitrate-N concentration has arrested the historical climb and declined an average of 0.1 mg/L/year for the 17-year history of the GWMA (Central Platte Natural Resources District, 2006).

US Corn Belt Case Study

The most-documented case of fertilizer to improve yield and thus water use efficiency (Viets, 1962) for rainfed cropping comes from the Mississippi River basin. The Mississippi River drains approximately 3.2 million km^2, which makes it the third largest river basin in the world. Within the basin are several highly productive agricultural regions, including the US Corn Belt, much of the US Great Plains, and the Lower Mississippi River Delta region; in total, 58% of the basin is cropland, with another 21% in rangeland. The central part of the basin produces the majority of the corn, soybean, wheat, cattle, hogs, and chickens in the USA (Goolsby and Battaglin, 2000). Annual runoff ranges from <5 cm/yr in the west to >60 cm/yr in the east. Much of the Corn Belt and the Lower Mississippi River Delta is either tile drained or surface-ditch drained. These areas are also among the most-intensively managed croplands in the USA. Annual fertilizer inputs to the Mississippi basin have increased from 0.4 million metric tons in 1950 to approximately 7 million metric tons in 1996 (Goolsby and Battaglin, 2000). Of the 133 smaller watersheds in the basin, those with higher N inputs correspond with those having higher estimated stream loadings, as expected. These higher-load watersheds are in areas with higher annual precipitation and with subsurface and surface drainage. Public concern about agricultural N losses has increased as a result of the mapping in 1985 of the northern Gulf of Mexico hypoxic zone and its subsequent expansion, which in 1999 extended to ~20,000 km^2 (Goolsby and Battaglin, 2000).

The high N fertilizer applications with maize have been confirmed to cause losses from tile drain pipes (Sawyer and Randall, 2005). Concentrations of nitrate-N ranged from 10 to 20 mg/L for maize-soybean rotations and from 15 to 30 mg/L for continuous maize.

The upper limits of these two ranges correspond to losses of 39 and 58 kg/ha of N, respectively. Although concentrations and loss values depend on fertilization, concentrations below the 10 mg/L drinking water standard cannot be achieved at economically optimum fertilizer amounts. For maize-soybean rotations, achieving the drinking water concentration required economic losses of US$14-67/ha. In continuous culture of maize, the drinking water standard was not met at any fertilizer level. The authors concluded that off-site practices would be needed to achieve 30% reduction in load, which has been proposed as a policy goal.

In Ohio, Fausey (2005) documented that restricting winter water movement through the simple step of inserting flashboard risers into tile drain outlets could prevent the loss of 30-50% of the nitrate lost from similar fields with the drains left open. Mean losses from conventional systems were 24 kg/ha of N for maize and 26 kg/ha of N for soybean, and were reduced to 13 and 14 kg/ha of N, respectively, from controlled drainage systems (Fausey 2005). This research has prompted the Agricultural Drainage Management System task force, a partnership among federal and state researchers and technical assistance agencies, to encourage with education and financial incentives this relatively simple approach to reducing nitrate-N losses to the Mississippi River basin.

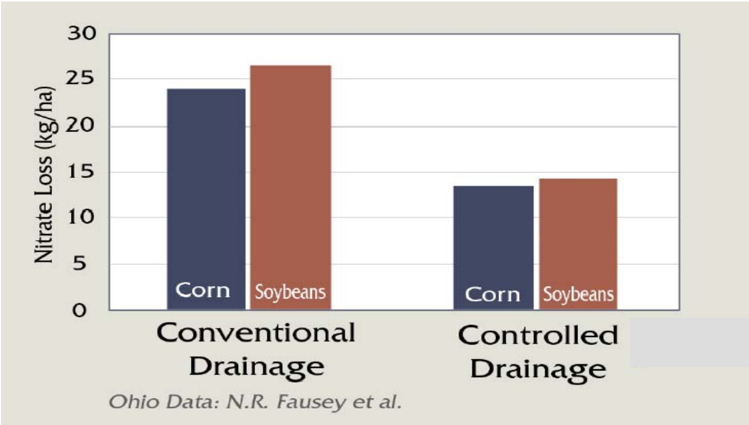

Figure 2. Annual nitrate loss from conventionally drained and controlled-drainage plots.

Lower Mississippi River Case Study

The Lower Mississippi River Valley (LMRV) delta extends from just north of the Ohio River confluence some 600+ km south toward Baton Rouge and New Orleans, Louisiana, and reaches some 120 km in width. In Missouri and Arkansas, the bulk of the delta is west of the river, and in Mississippi, it lies east of it. In Louisiana, the river again runs east, leaving the delta to the west. In the late 1800's, the cypress swamps were harvested for timber, and in the first half of the 1900's, most of the delta was drained with an extensive surface ditch network. This project made approximately 70,000 km^2 of land available for cropland; nearly half is irrigated. Primary crops grown in this area include soybean, cotton, rice, corn, grain sorghum, and wheat. There is little to no topographic relief, and elevations decrease gradually from roughly 100 m at the north end to roughly 15 m at the south. Because of the extensive surface drainage, the drainage issue mentioned above may need to be considered. Testing for loss of nitrate during the winter period is currently being pursued. If appreciable nitrate is detected during flow events, rigorous monitoring will be initiated to provide data for policy decisions.

The LMRV has more than 2.9 million ha of irrigation, including furrow irrigation, center pivots, and rice paddies. Approximately half of this has been put into place since 1980, with the bulk of the irrigation prior to that being in Arkansas. The LMRV is the primary region in the USA where irrigated area is increasing; the western states have shown a consistent slow decline in irrigated area because of pressure from non-agricultural water users. (US Census of Agriculture, 2002). There is substantial interest in improving efficiency of water use, especially for rice production.

Rice production in this area is usually achieved with either level fields with more or less permanent levees surrounding them, or with temporary levees at equal elevations down a gradient. In the latter case, conventional irrigation practice is to flood the uppermost paddy and let water cascade over spillways into the next-lower paddy. As successively lower paddies fill, water eventually fills all paddies in the field. At this point, the pump is stopped until ET and percolation cause a need for the process to be repeated. In an alternative known as multiple-inlet rice irrigation (MIRI - Vories et al. 2005b), a pipe is run down the gradient to the lowest paddy. For each paddy, an individual gate is opened, so that all paddies fill concurrently. In the field test of this system in Arkansas, the MIRI approach required 24% less irrigation water and increased yield 3%, producing a 36% increase in irrigation water use efficiency (Vories et al. 2005b). As competition for water supplies is a critical issue in this area, federal technical service providers have proposed that this technique be adopted for financial incentives as a water-conserving measure (Vories, personal communication, 2005). Studies are now examining the water-quality impacts of the MIRI system (Vories et al. 2005a).

US Southeast Atlantic Coastal Plain Case Study

The southeast Atlantic Coastal Plain extends from the Chesapeake Bay and the Delmarva Peninsula in Delaware-Maryland-Virginia southward, crossing northern Florida, to southern Alabama. It extends on average 150-200 km from the Piedmont (front range of the Appalachian Mountains) to either the coast or to the Florida peninsula, which comprises a separate physiographic region. Elevations slope from the coast up to 70-100 m at the Piedmont. On the order of 150,000 km^2 lies in this area, which is somewhat intensively farmed, but not nearly as much so as the LMRV or the US Corn Belt. Higher population densities and reliance on multiple land uses, including native or planted forests, tourism, urbanized areas, and many industrial areas, reduce the proportion of this area used for cropland.

Soils in the Coastal Plain are generally sandy in the surface layers and underlain by clayey subsoils. Dense hard pans in the lower surface layer and sometimes acidic subsoils restrict rooting volume, which when combined with low water holding capacity of the surface layers, cause frequent but brief periods of significant water stress. Therefore, despite high annual average rainfall of ~1000 mm, irrigation is often needed. Research in South Carolina indicated that 16-year average summer rainfall was 250 mm less than calculated potential ET. This deficit usually reduces the soybean, cotton, and corn yields in the area. For economic and societal reasons, in this region, only Georgia and Florida have invested extensively in irrigation (US Census of Agriculture, 2002).

Another characteristic of coastal plain soils is that they exhibit substantial spatial variation. At prevailing average sand contents of 70-80% for sandy loam and loamy sand soils, a small change in clay content in the surface layer can result in a large difference in water holding capacity and hydraulic conductivity.

The region is dotted with shallow depressions with higher clay contents (e.g., loams or sometimes clay loams or clays). Most fields, and thus most irrigation systems, encompass areas of such contrast. Irrigation management under these conditions is difficult; irrigating perfectly for the main soil type assures doing it sub-optimally for the others. These challenges prompted research in South Carolina into site-specific, or precision irrigation (see Camp et al. 2002; Sadler and Camp 2002 for overviews). Two commercial center pivots were modified to achieve independent irrigation depths on areas 9 x 9 m (Omary et al. 1997; Camp et al. 1998). With these machines, two experiments on irrigation by N management were conducted during 1999-2001. Camp et al. (2002) presented combined irrigation and N management results from both pivots, and Lu et al. (2004) presented the combined economic analyses for water and N from these data. Sadler et al. (2005) presented maps of profit-maximum yield and the irrigation requirements to show potential for conserving 16-32% of water. From these data, figure 3 presents the marginal benefit of irrigation applied (also called IWUE) for the profit-maximizing case in 1999 for two levels of N treatments, which clearly illustrate the interactions between N and water, both in the 25% increase in the field-mean value with irrigation, and in the changed patterns of IWUE within the field.

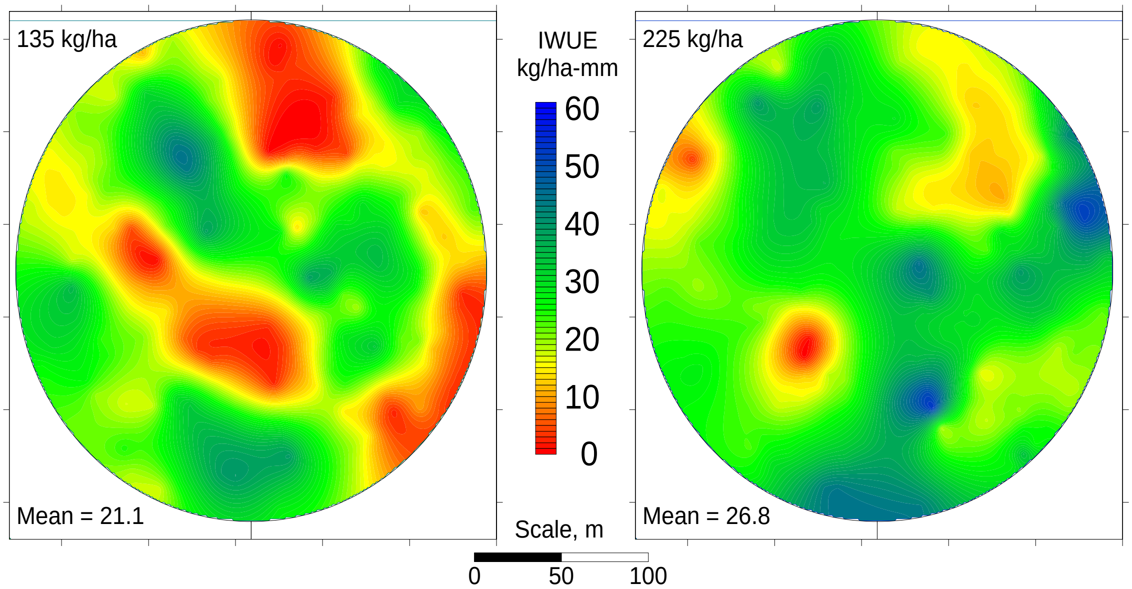

Figure 3. Estimated Irrigation Water Use Efficiency (IWUE) of profit-maximized maize for two N levels. Data from Sadler et al. (2005). Mean yields are 9.36 and 10.68 Mg/ha; mean irrigation values are 182 and 208 mm.

Summary and Conclusions

A general discussion of the research to improve water use efficiency illustrated the successes and failures achieved in the US during the past half-century. We can take the presence of fertilizers in streams to indicate that improving water use efficiency by adding fertilizer has caused less-than-optimum N use efficiency. We hope the extent of this problem in the intensively managed cropland in the USA can serve as a counter-example to other regions in the world seeking to maximize yield per unit of applied water. Ideally, a dual optimum, considering both irrigation and fertilization, can be found that reduces adverse environmental effects for future generations to address. Findings in the above-mentioned case studies and similar research worldwide should suggest potential solutions for economically and environmentally sustainable agriculture.

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