STRATEGIES TO IMPROVE PRODUCTIVITY IN A WATER-STRESSED FUTURE

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ABSTRACT

As water shortages become more commonplace, strategies to increase crop water productivity are increasingly sought by producers. Common strategies include increasing irrigation application efficiency, changing irrigation application methods, improving irrigation scheduling, using sensing systems to guide management, changing forage crops, and managing for moderate, controlled deficit irrigation. These strategies improve productivity by reducing runoff and deep percolation losses, applying water more uniformly so that severe deficits do not occur in some parts of the field and waterlogging in other parts, reducing evaporative losses of water by applying water close to or beneath the soil surface, changing the crop-specific transpiration efficiency, and managing for maximum water use efficiency (unit of yield per unit of water consumed) rather than maximum yield. This paper discusses examples of the use of one or more of these strategies to successfully increase water productivity of forage crops.

Key words: water use efficiency, crop water use, yield, irrigation application method

INTRODUCTION

Water shortages are the present and likely future condition of western irrigated agriculture, which contributes >$117 billion of annual farm gate production value and total economic impact of $156 billion. Nationally, 40% of crop market value is produced by irrigation on only 7.5% of cropped lands. To sustain and improve agricultural productivity requires increases in irrigation efficiency and crop water productivity, also known as water use efficiency. Irrigation efficiency is the ratio of water consumed by the crop through evapotranspiration (ET) to the irrigation water applied. Reducing runoff and deep percolation losses are ways in which to increase irrigation efficiency. Water use efficiency (WUE) or crop water productivity (CWP) is defined as the economic yield obtained per unit of water consumed by the crop. Ways to change CWP include choice of crop and variety, irrigation scheduling and amount, irrigation method and management, fertility management, tillage management and soils and climate.

$$\text{CWP} = Y/(E + T) = \text{transpiration efficiency}/(E/T + 1)$$

where Y is economic yield, E is evaporation, T is transpiration, and the transpiration efficiency is Y/T. Generally, the C4 crops such as corn and sorghum will produce more yield per unit of ET

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than will a C3 crop such as wheat due to the larger transpiration efficiency of C4 crops. Timing of water supply has a large effect on CWP. An otherwise well-watered crop that is short of water during a critical growth period will suffer decreased yield and CWP. Examples are corn that is short of water during silking and wheat that is short of water during flowering and grain fill. Irrigation method can influence WP by affecting the ratio of evaporative loss to crop transpiration. Irrigation methods that reduce soil and crop wetting, and thus evaporative losses, include subsurface drip irrigation and low-energy-precision-application (LEPA) applicators on sprinkler irrigation systems.

The role of irrigation in increasing CWP is perhaps the major reason that agricultural production in the western states overshadowed that in the eastern states as the west was settled. Production agriculture in the west is by necessity almost entirely irrigated. In general, the CWP of irrigated crops is twice that of non-irrigated crops, and the same is true for forages. In the High Plains, wheat yield and water use efficiency are doubled when irrigated rather than grown as a dryland crop (Fig 1A, Musick et al., 1994). The same is true for sorghum yield in the High Plains. Elevations (3,500 to 4,000 ft) and climate (semi-arid, continental) are similar in the High Plains to those in much of the forage producing areas of the intermountain West.

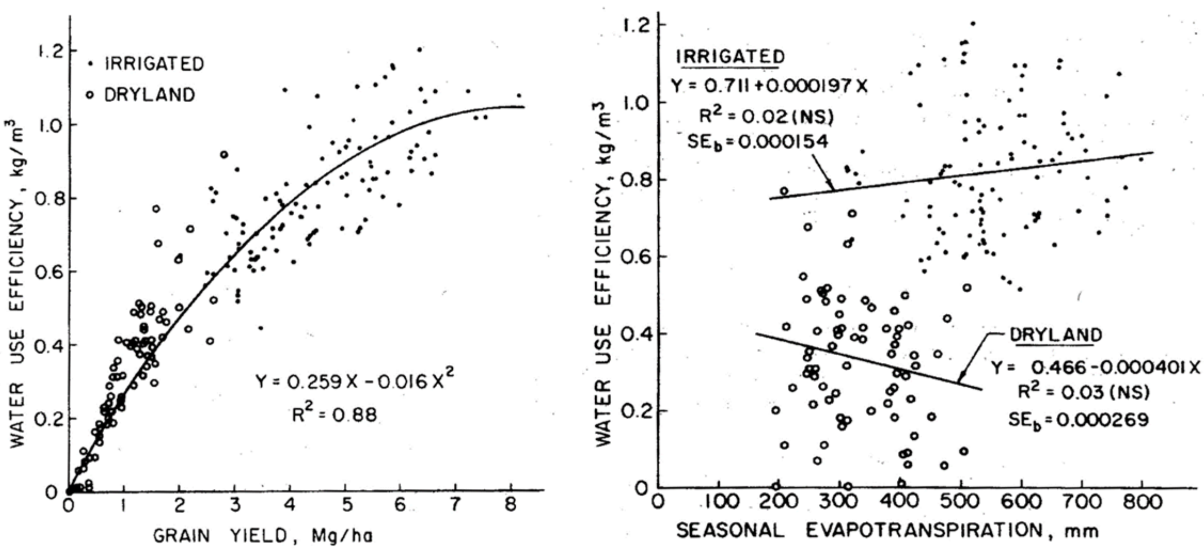


Figure 1. Winter wheat water use efficiency as functions of grain yield and season evapotranspiration (Musick et al., 1994).

The role of irrigation in increasing agricultural productivity in American agriculture cannot be overemphasized. Since the late 1940s, the total factor productivity of agriculture has increased 2.5 times while agricultural input growth has remained nearly stable (Fig. 2A). The enhanced productivity is tied to improvements in crop genetics and fertilization (the green revolution) and to the rapid growth of irrigated lands (the blue revolution). It is arguable that the blue revolution of irrigation was the major factor in productivity increases. When irrigated land increased productivity increased, and periods of decreased or stable irrigated area were accompanied shortly thereafter by decreased or flat productivity gains (Fig. 2B). In particular, since 1998, U.S. irrigated area has remained nearly constant at 55-56 million acres, and this was accompanied by a slowdown and eventually a stabilization of productivity growth.

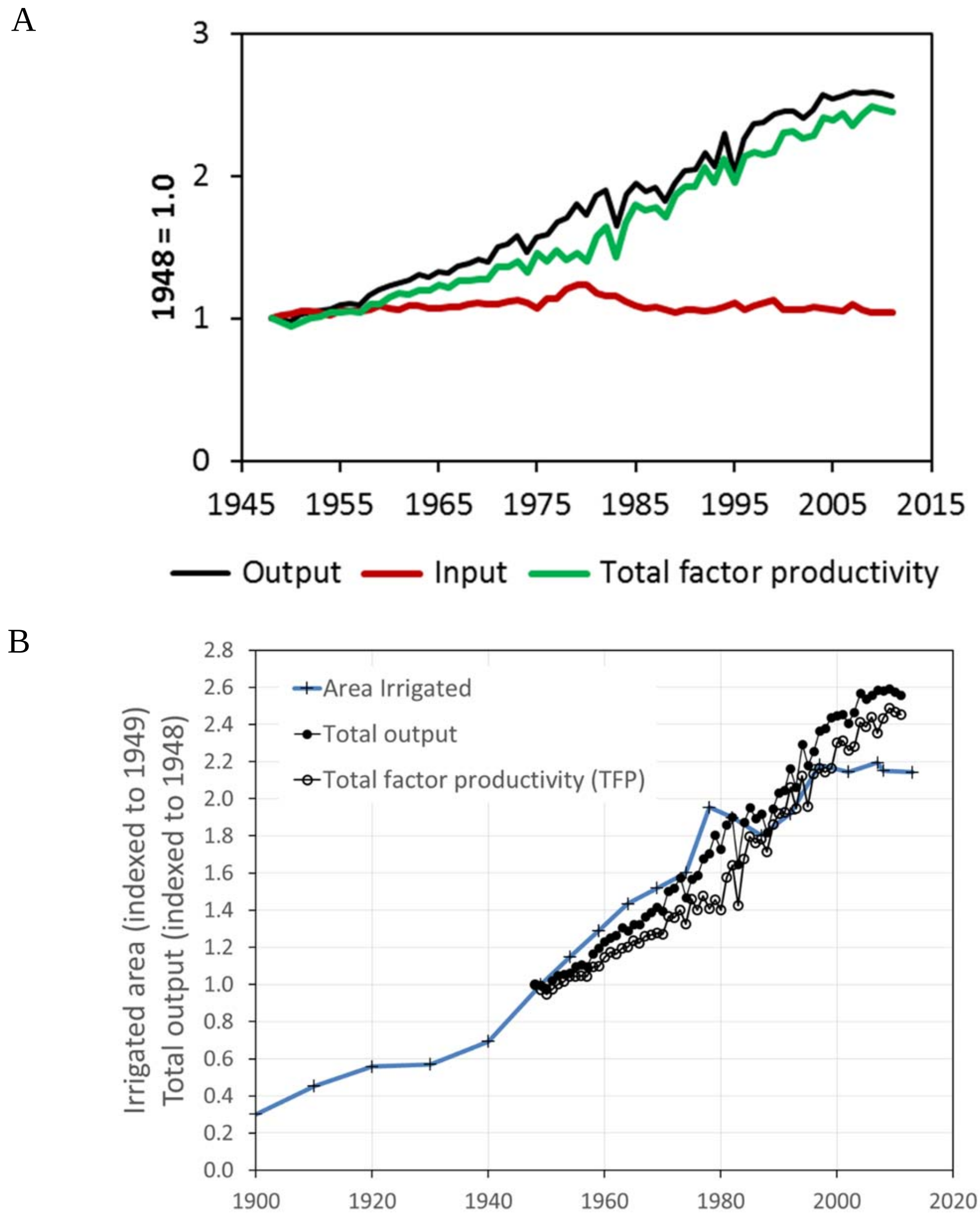
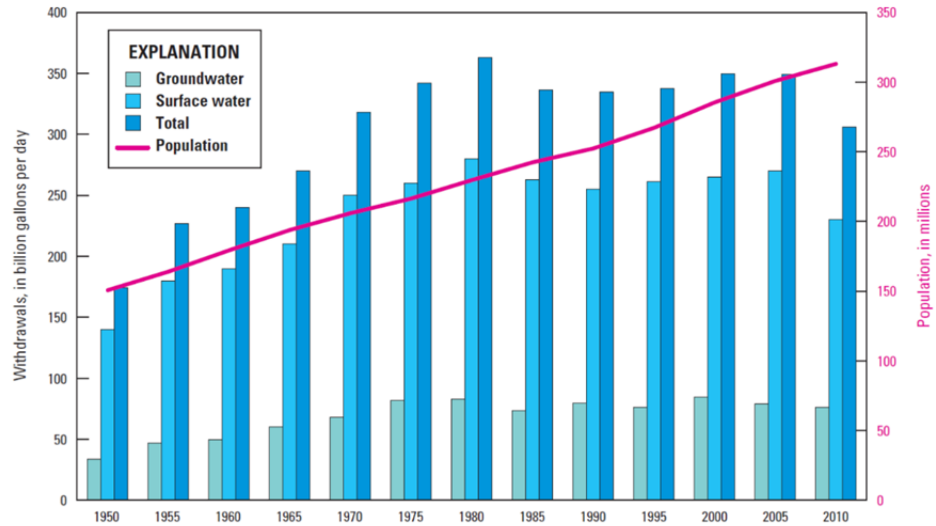


Figure 2. (A) United States agricultural output, input and total factor productivity scaled to 1948 values. (B) Increases in U.S. irrigated area scaled to 1949 values, and total output and total factor productivity scaled to 1948 values. (NASS, 2013)

However, since circa 1969, a second blue revolution has been at work, leading to increased productivity as irrigation water withdrawal increases slowed and then stopped, with irrigated withdrawals remaining practically stable and even declining since 1980 (Fig. 3A). The stabilization and even decline of freshwater withdrawals for irrigation coincided with: 1) a rapid increase in the percentage of land irrigated using pressurized systems (sprinkler and microirrigation) from 18.4% in 1979 to 65.2% in 2012; and 2) a corresponding decrease in the annual depth of irrigation applied from 25.2 to 19.2 inches (640 to 490 mm).

A



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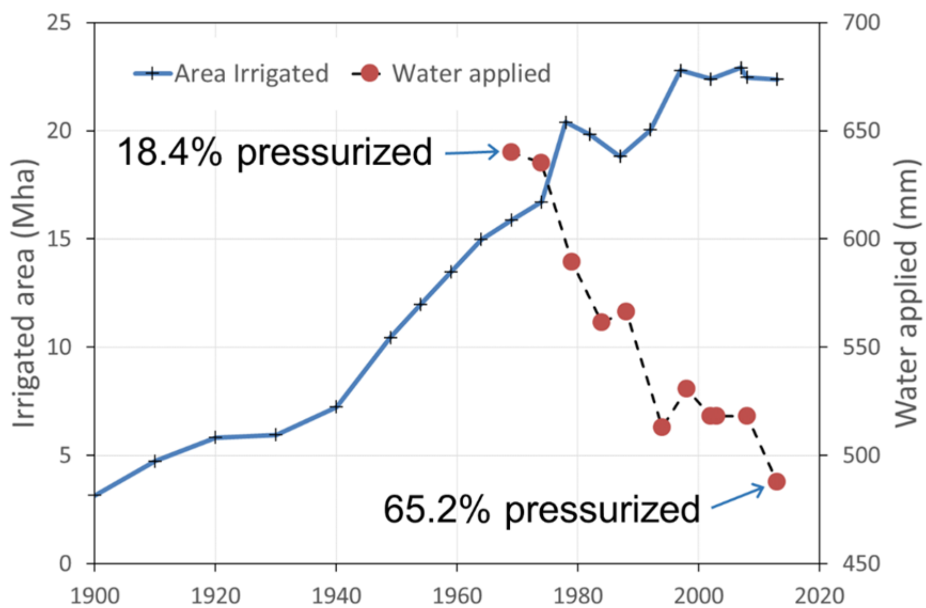

Figure 3. (A) U.S. irrigation withdrawals and population from 1950 to 2010. (B) U.S. irrigated area and average depth of annual irrigated applied. (ERS, 2002, NASS, 2013)

This rapid increase in the use of pressurized irrigation systems has included growth of microirrigation since 1979 to presently in use on 9% of U.S. irrigated lands (Fig. 4). The increase in irrigation efficiency and CWP has, however, come at a cost. Producers spent $2.6 billion on expenses related to irrigation equipment, facilities, land improvements and computer technology in 2013 (NASS, 2013). Of those expenses, 50 percent was for replacement of existing equipment, 35 percent for new expansion and 15 percent for water conservation. Energy expenses for irrigation pumping were $2.7 billion in 2013, which includes both lifting water from wells and water bodies and pressurizing irrigation systems.

Compared with gravity flow irrigation, productivity improvements with pressurized irrigation systems arise from more uniform irrigation applications that can reduce deep percolation losses and runoff while preventing over application and water logging in some parts of the field and under irrigation in other areas. Producers also commonly find that sprinkler or drip irrigation can be accomplished with smaller water flows than are required to properly irrigate using gravity flow.

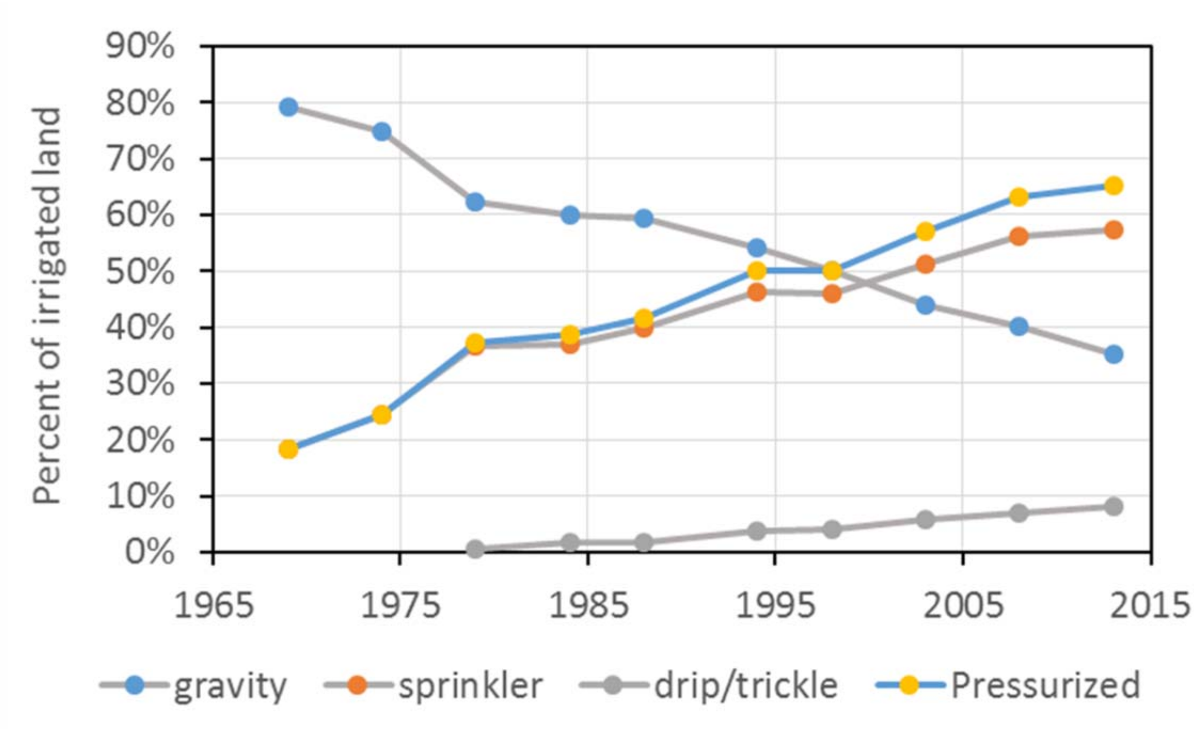

Figure 4. Percent of irrigation land in gravity flow, sprinkler, drip and trickle (microirrigation), and the total percentage of land irrigated by pressurized irrigation systems (sprinkler, drip and trickle) (NASS, 2013).

Forage yields are as reliant on a stable water supply for increases in yield and CWP as are yields of grain crops. In the western states (largely west of the 95^{th} meridian), non-irrigated forage yields are roughly 1 ton/acre less than those in the eastern states (Fig. 5). However, in the western states where >31% of forage lands are irrigated, yields are roughly three times greater than those achieved on non-irrigated lands and considerably larger than those achieved in the east where most forage is not irrigated. Only 1% of forage land in the east is irrigated.

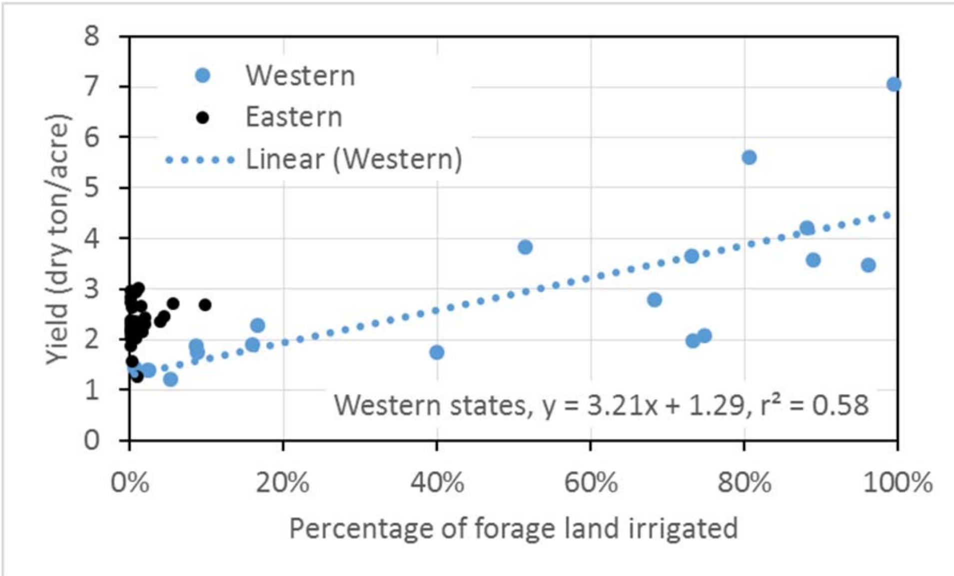

Figure 5. Forage yield as a function of percentage of forage land irrigated for the 19 western states and the 31 eastern states. (NASS, 2013)

WATER SAVINGS WITH MICROIRRIGATION

Compared with gravity and sprinkler irrigation methods, microirrigation of forage crops, particularly subsurface drip irrigation (SDI), can reduce water consumption for a given yield target by decreasing evaporative losses. Sorghum and corn grown at Bushland, Texas with both mid elevation spray application (MESA) sprinklers and SDI showed that savings of 2.1 to 2.5 inches of water could be achieved during the period of pre-plant irrigation through 25 days after planting when plant cover became important (Fig. 6). Another 2.1 to 2.6 inches of water were saved in midseason with SDI due to evaporative losses from the plant canopy that occurred with MESA irrigation. Improvements in WUE ranged from 11% for sorghum to 44% for corn. Although WUE was computed for grain yield in these experiments, similar differences in biomass were observed.

Alfalfa has shown considerable increases in both yield and CWP when irrigated with SDI compared with flood or furrow irrigation. This has been shown at a wide variety of locations including Lubbock, TX; NM; Coolidge, AZ; Kansas; Lovelock, NV; the Treasure Valley, ID; and the Imperial Valley and Tulare Lake areas, CA. Advantages other than reduced evaporative losses include elimination of leaf scalding that may occur with sprinkler irrigation; quicker turnaround of harvest operations due to firmer soil, which allows irrigation to be resumed more quickly; and larger yields (Alam et al., 2009). Because irrigation can be continued nearly up to and, depending on soil type, during harvest, irrigation system capacity can be smaller and still achieve adequate irrigation for high yield. Although improvements in alfalfa yield and CWP are clear for SDI, drip tape damage by rodents can be severe in some locations (e.g., the Treasure Valley, Idaho, Neufeld, 2014; Coolidge, AZ, Blake, 2009). Longevity of SDI systems is a concern, but SDI installed at both Colby, KS, and Bushland, TX, has lasted >20 years, well beyond the amortization period for the systems and competitive with center pivot irrigation systems in total cost over the life of the system.

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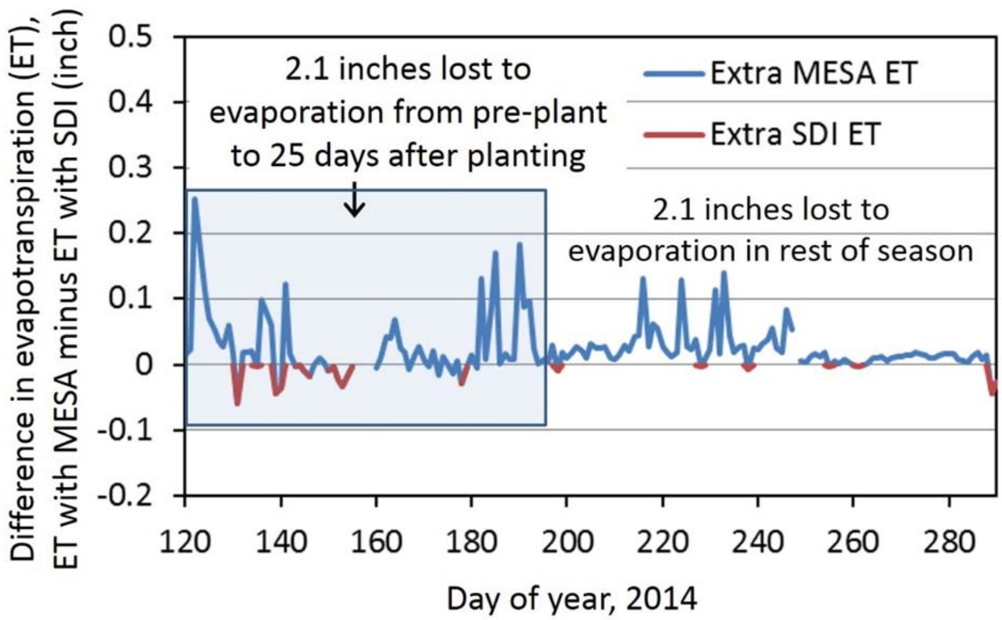

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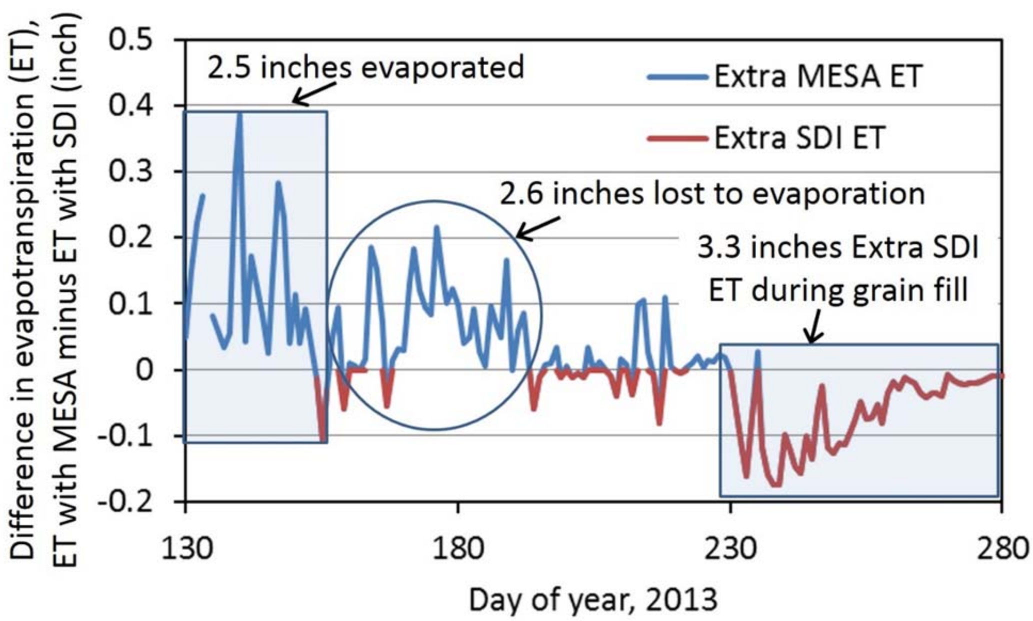

Figure 6. Differences in evapotranspiration (ET) between sprinkler (mid elevation spray application, MESA) irrigation and subsurface drip irrigation (SDI) at Bushland, Texas. Blue indicates greater ET from MESA irrigation and red indicates greater ET from SDI. (A) Results for sorghum irrigated in 2014. (B) Results for corn grown in 2013.

YIELD AND CROP WATER PRODUCTIVITY INCREASES WITH ADVANCED CENTER PIVOT MANAGEMENT

The increased percentage of irrigated land that is sprinkler irrigated (from 19% in 1969 to 56% in 2013) coincided with large reductions in annual irrigation amounts that were only feasible because of the greater uniformity of irrigation with these systems when properly set up. Irrigation scheduling remains, however, largely based on producer perceptions of crop water needs, sometimes backed up with soil water sensors of various types and accuracies, or weather based scheduling programs based on a daily reference ET, ETo, and a crop and crop growth stage specific crop coefficient, Kc, where daily crop water use, ETc, is calculated as ETc = Kc × ETo. The reference ET is calculated from weather station data using, for example, the standardized Penman-Monteith reference ET method (ASCE, 2005). Typically, this procedure gives ETc for a well-watered crop managed for high yields. It is well known, however, that greater CWP and often greater profitability can be obtained by irrigating at less than the well-watered rate, so called deficit irrigation. Well managed deficit irrigation reduces crop yields only slightly (e.g., 5%) or not at all, but reduces pumping costs and nutrient losses that can occur due to deep percolation and runoff occurring in some parts of fully irrigated fields.

Producers often avoid deficit irrigation for reasons ranging from the risk of considerable yield losses if management is imperfect and the crop suffers to uncertainty about irrigation capacity being large enough to keep up with crop water demand during peak water use periods, and to uncertainty regarding the accuracy of ETc estimates made using the crop coefficient-based scheduling method. Alternative scheduling methods based on plant water stress sensing are, however, showing the ability to manage deficit irrigation without undue crop yield reductions while increasing CWP and sometimes yield. Most recently, these methods rely on wireless sensor networks of thermal infrared sensors to monitor crop canopy temperature in the field, transferring the data automatically and wirelessly to an embedded computer at the pivot point where the data are processed to produce recommendations for irrigation automatically (Fig. 7A). Recommendations can be for an entire field, or in the case of a VRI system, a prescription map can be uploaded to the center pivot control panel (Fig. 7B). Earlier versions of this system showed good control of WUE and yield using drip irrigation systems (Evett et al., 2001, 2006).

An Irrigation Scheduling Supervisory Control and Data Acquisition System (ISSCADAS) was developed and patented by USDA ARS to enable sensor-based irrigation scheduling based on automatic sensing and irrigation needs assessment (Evett et al., 2014). The system uses geographical positioning systems (GPS) to allow dynamic spatial mapping of plant water stress and corresponding irrigation scheduling prescriptions (O’Shaughnessy et al., 2015). Current versions of ISSCADAS use a wireless sensor network and computer algorithms to determine irrigation needs based on a crop water stress index integrated over daylight hours (iCWSI). In a series of experiments, O’Shaughnessy et al. (2012a,b) showed that ISSCADAS obtained sorghum and cotton yields and WUE values as large as and sometimes larger than those obtained using weekly neutron probe readings for irrigation scheduling (the latter including data from Colaizzi et al., 2004). In particular, sorghum yield and WUE were typically larger for moderate deficit irrigation (55 to 80% of full) compared with full irrigation (Fig. 8A,B). A graphical user interface (GUI) is being developed to allow easy use of the system by producers (Andrade et al., 2015).

A

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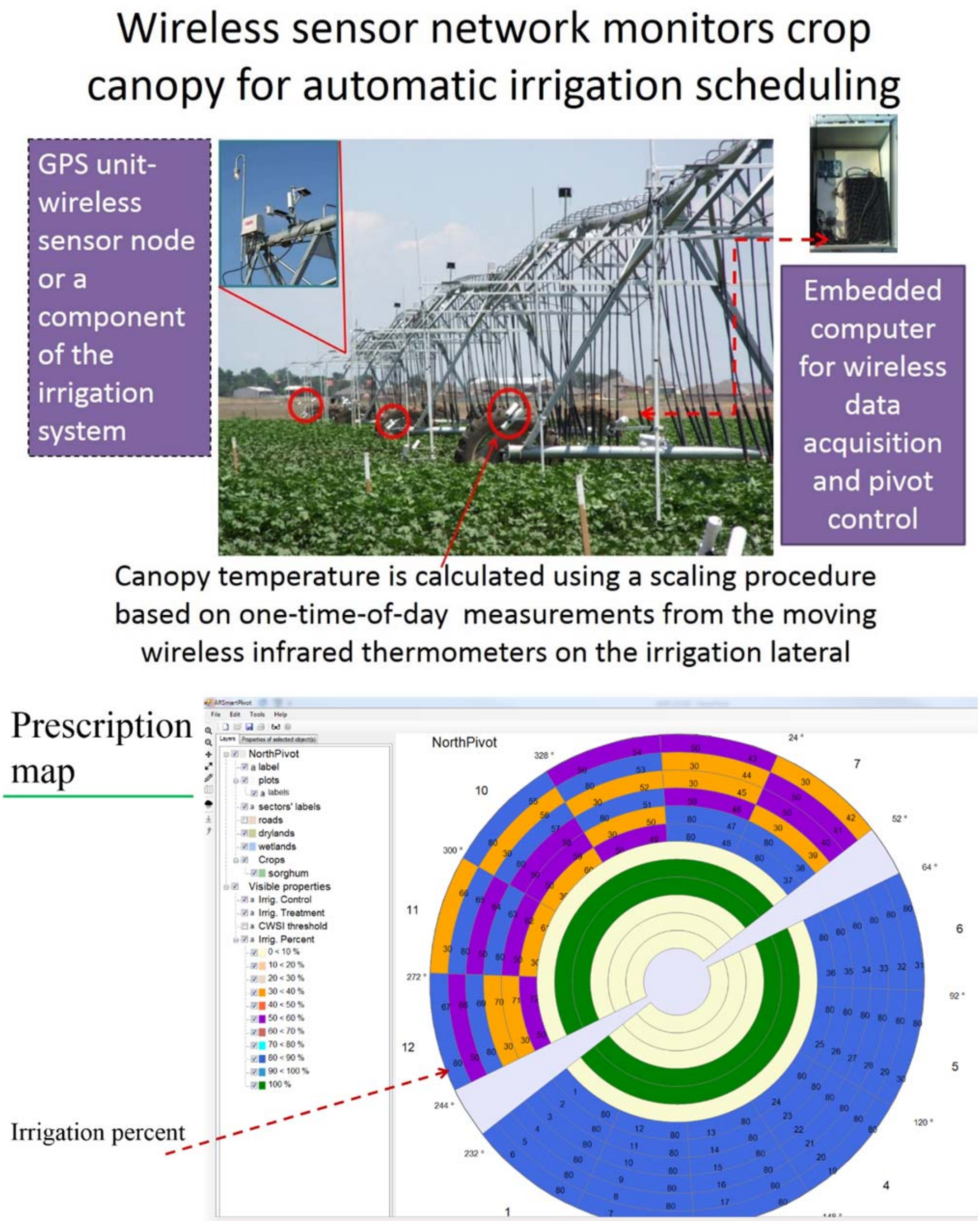
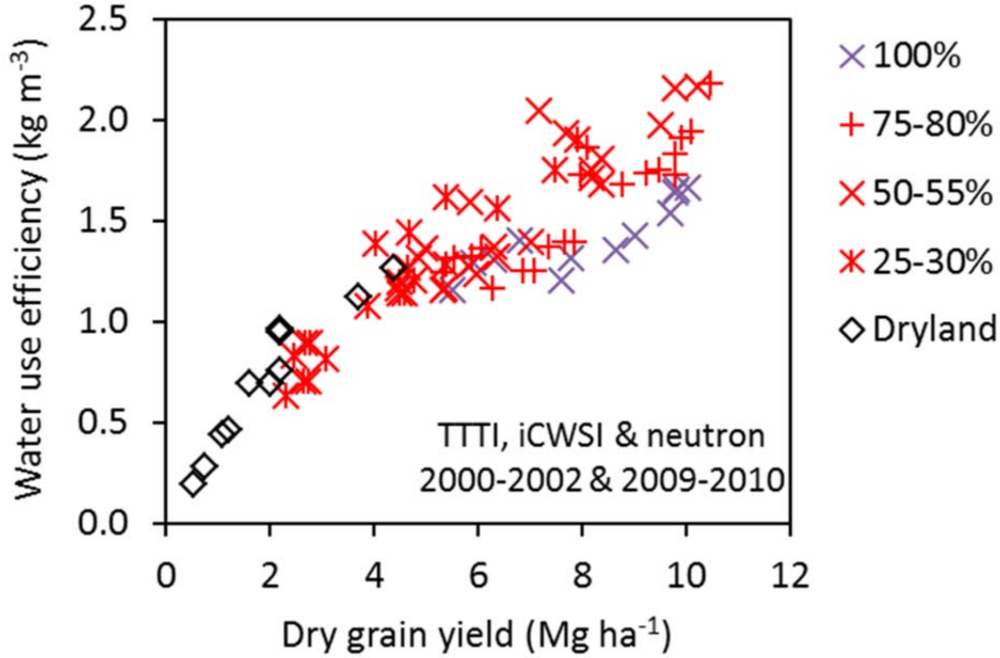


Figure 7. (A) A variable rate irrigation (VRI) center pivot system combined with a wireless network of crop canopy temperature sensors (thermal infrared) and an embedded computer running a supervisory control and data acquisition (SCADA) software to automatically determine full and deficit irrigation levels and control the VRI system. The pictured system is at the USDA, ARS Conservation & Production Research Laboratory, Bushland, Texas. (B) Example of a prescription map produced by the ARS Smart Pivot software (Andrade et al., 2015).

A



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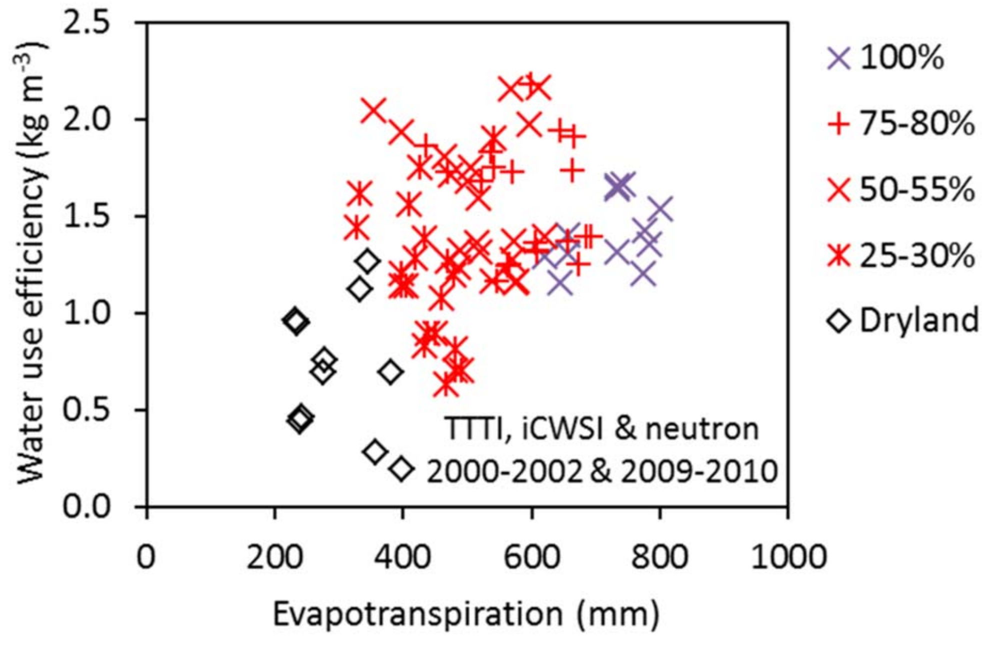

Figure 8. (A) Water use efficiency versus grain yield for sorghum irrigated using three irrigation scheduling methods, the integrated time-temperature threshold (TTTI), the integrated crop water stress index (iCWSI), and the neutron probe at full (100%) and deficit irrigation levels. (B) Water use efficiency versus crop evapotranspiration for the data shown in Fig. 7A.

ADVANCED WIRELESS SENSOR SYSTEMS FOR IRRIGATION MANAGEMENT

Numerous plant and soil sensor systems have been developed in the past 20 years, but utilization in producer fields has been hampered by the wiring required to get data from sensors to where it can be used for management. Recently, wireless sensor networks have been developed and adapted to irrigation system management. A recent wireless plant canopy temperature sensor was developed in cooperation with USDA ARS at Bushland, Texas (Fig. 9A). This sensor was developed in conjunction with the work reported by O'Shaughnessy et al. (2012a,b). In 2015, a novel soil water sensor based on a miniaturized time domain reflectometry electronic circuit was patented (Evett et al., 2015) and one of several sensors based on this true TDR circuit was introduced commercially (Fig. 9B). This sensor can be easily field deployed in a wireless sensor network based on commercially available wireless dataloggers. Advantages over previous soil water sensors include accuracy sufficient for irrigation management based on management allowed depletion (MAD) concepts, and nearly complete immunity to soil electrical conductivity and temperature problems (low sensitivity at solution conductivities less than 7 dS m^{-1}; Schwartz et al., 2015). A version for installation in auger holes is planned, and a version for deep profile water content sensing using a plastic access tube is in development. The latter waveguide on access tube (WOAT) design will allow water content sensing using 8-inch segments that can be connected as desired in increments to depths throughout the root zone and below.

A

B

Figure 9. (A) A wireless thermal infrared thermometer intended for crop canopy temperature measurements in a wireless sensor network (model SAPIP-IRT[2], Dynamax, Inc., Houston, Tex.). (B) A true time domain reflectometry (TDR) sensor (model TDR-315, Acclima, Inc., Meridian, Idaho) intended for irrigation management and compatible with wireless dataloggers

[2] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

(e.g., model CR206X, Campbell Scientific, Inc., Logan, Utah).

SUMMARY

Strategies to improve agricultural productivity in the face of water limitations range from choice of crop, tillage and agronomic methods that conserve water and utilize it more efficiently to adoption of irrigation application methods that more uniformly apply water, reduce or eliminate conveyance losses and reduce evaporative losses from wetted canopy and soil surfaces. Sprinkler systems equipped with low-elevation-precision-application (LEPA) and low-elevation-spray-application (LESA) devices can reduce evaporative loss from wetted canopies and to some extent from soil surfaces when used in every other crop interrow, but can cause runoff problems. Subsurface drip irrigation (SDI) eliminates losses from canopy wetting and most losses due to evaporation from the soil surface, resulting in increased crop water productivity and allowing high yields with less water pumped. In some cases, yields are larger with SDI than are possible even with full irrigation using gravity methods. Advanced irrigation systems utilizing wireless sensor systems to automatically determine crop water stress have been shown to improve crop water productivity and allow well-regulated deficit irrigation with little user effort. When used with variable rate irrigation systems, these advanced supervisory control and data acquisition (SCADA) systems can allow spatially varying application of irrigation water to avoid flooding low lying areas and to respond to water stress where it occurs in the field. Combined with ever improving wireless plant and soil water sensing systems, SCADA control is poised for rapid commercialization and application in producer fields.

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