IMPROVEMENTS IN WATER USE EFFICIENCY IN IRRIGATED COTTON: CHOICES IN SYSTEMS AND MANAGEMENT

R. B. HUTMACHER[1], C. J. PHENE[1], K. R. DAVIS[1], W. R. DETAR[2] & J. E. AYARS[1]

1 - USDA-ARS Water Management Research Laboratory, 2021 S. Peach Avenue, Fresno, CA 93727, USA
2 - USDA-ARS U.S. Cotton Research Station, Shafter, CA, USA

Abstract

Major factors (crop, soil, topography, labor and management availability and skill, environmental concerns, regulatory controls, economic) influencing irrigation efficiency, water use efficiency and the choice of appropriate irrigation systems and management for cotton are reviewed and discussed. One field experiment in the San Joaquin Valley of California which identifies the high yield potential, relatively low water use, and high water use efficiency possible under subsurface drip irrigation is described in detail. Three different field experiments and grower experiences in evaluating different irrigation systems (furrow versus subsurface drip in all three, center pivots included in one grower evaluation)in terms of water requirements, water use efficiency and potential for minimizing deep percolation are reviewed in the context of options for improving water use efficiency in fully-irrigated cotton under conditions in the western United States. Drip irrigation is discussed in detail but remains only one of the choices for changes in irrigation systems and management that are available to improve irrigation efficiency and water use efficiency while maintaining a favorable net economic return.

Introduction

One of the distinguishing characteristics of cotton production in several regions of the western United States is the need for irrigation in order to achieve acceptable cotton production levels and profits. Most parts of traditional cotton production areas in California, Arizona, and New Mexico and some parts of Texas cannot achieve profitable cotton production without supplemental irrigation. Most of these areas have annual rainfall ranging from as low as 60 mm to over 300 mm. With crop evapotranspiration of at least 550 mm in most of these production areas and over 900 mm in some of the more arid zones, it would not be possible to achieve profitable cotton production without irrigation. Cotton varieties in these areas have been selected for production under irrigated conditions, so considerable effort has been directed toward sustained cotton production systems that require irrigation.

The average crop evapotranspiration (ET_c) of furrow-irrigated cotton in the San Joaquin Valley of California has been identified as ranging from 31 to 33 inches (785 to 840 mm) (California Department of Water Resources and Univ. of California Coop. Ext., 1980; Grimes *et al.*, 1969; Grimes, 1982). Irrigation amounts considerably in excess of 800 to 900 mm are quite common for cotton in central CA (Phene *et al.*, 1992). The high application uniformity and control of deep percolation possible with drip irrigation, particularly subsurface drip irrigation, however, has demonstrated that high yields (in excess of 2000 kg lint ha^{-1}) can be achieved even with 25 to 28 inches (635 to 710 mm) of ET_c in clay loam soils of the San Joaquin Valley (Phene *et al.*, 1992; Hutmacher *et al.*, 1993).

Bucks *et al.* (1982), Phene *et al.* (1987), and Bar-Yosef *et al.* (1991, 1992) have reviewed many of the potential advantages of drip irrigation in row crops and management requirements for successful use of drip irrigation. A number of studies conducted at the

USDA-ARS Water Management Research Laboratory in Fresno, CA (Bar-Yosef *et al.*, 1992; Hutmacher *et al.*, 1993) have shown that although very high lint cotton yields can be achieved with drip irrigation, maintenance of acceptable nutrient availability is critical to achieving high plant growth rates and favorable yields. Under furrow irrigation, fertilizers are typically broadcast or banded pre-plant, with one or more supplemental side-dress applications made later in the season. Soluble nutrients are more susceptible to deep percolation losses when plant uptake is separated for a long time period from the time of application.

In subsurface drip irrigation studies of Bar-Yosef *et al.* (1992), Phene *et al.* (1992), and Hutmacher *et al.* (1993), nitrogen and phosphorus fertilizers were injected continuously with the irrigation water during most of the irrigation season, while potassium applications were concentrated during the boll development and maturation stages. High frequency water and nutrient applications avoid even minor water and nutrient stresses. In crops where harvestable yield is highly correlated with total biomass, avoidance of even minor stresses can be beneficial in achieving high yields. In cotton, where a balance between vegetative and reproductive growth is critical to producing and retaining bolls, an irrigation program that minimizes water and nutrient stress may achieve high biomass production but may not achieve high yields and high water use efficiency (Phene *et al.*, 1992; Hutmacher *et al.*, 1993).

Choice of the "best" irrigation system was never a simple choice in production of any crop, but in recent years the choice is becoming even more difficult. Growers may consider alternative irrigation systems when operation of older systems becomes cost-prohibitive or when extensive repairs or other expenses are required to continue with the same irrigation method. Economic, physical, biological and regulatory factors all can have a major role in deciding not only what irrigation options cost, but also, which options can even be considered.

Irrigation is a major portion of the total cost of production in many cotton production areas. Costs of irrigation can be strongly affected by costs and availability of labor, energy, and money for capital improvements. In some areas such as parts of Arizona and the Ogallala aquifer area of the western Great Plains of the U.S., water resources available to farmers are being reduced due to declining groundwater supplies, higher energy costs for pumping, and regulatory controls. In many states, agricultural water users are in competition for limited water supplies with municipal, industrial, recreation and wildlife water interests. In California, farmers have routinely used groundwater supplies to supplement or replace surface water supplies, with two million acre-feet a common statewide groundwater overdraft in typical years, increasing to over 10 million acre-feet during serious drought years (such as during the recent drought of 1986 through 1991). Although recharge efforts can replace some of this overdraft in years with abundant water supplies, this type of overdraft without full recharge cannot go on indefinitely.

Under current economic and regulatory conditions, development of new water supplies through diversions of rivers or construction of new dams will be extremely limited, so there are few significant, economically- or socially- acceptable sources of additional irrigation water in many Western states. Portions of the Clean Water Act and Endangered Species Act of the U.S. Federal Government stipulate protection of water supplies for maintenance of specific minimum standards for water flow and water quality. Together, these and other regulatory actions have significant potential to both divert some existing water supplies to non-agricultural users and impose standards for volume and quality of agricultural drainage waters.

Whether or not any irrigation management program (combination of the choice of irrigation system and how it is managed) is judged successful will depend on a wide range of economic, agronomic, environmental, and engineering factors. This work will: (1) review and discuss some principal factors influencing water use efficiency and the potential for improvements in irrigation efficiency and water use efficiency; (2) identify the role of changes in management versus hardware in attempts to improve water use efficiency; and (3) discuss some recent comparisons of water use efficiency in cotton grown under several irrigation systems in the San Joaquin Valley of California.

Cotton has traditionally been irrigated by furrow methods in much of the arid and semi-arid western U.S. Sprinkler irrigation using center pivots and linear-move sprinkler systems is also a well-established and well-research cotton irrigation method in areas such as the Texas High Plains. In recent years there have also been a number of evaluations of drip irrigation for cotton production in the western U.S. (Wilson *et al.*, 1984; Phene *et al.*, 1992; Hutmacher *et al.*, 1993). Concerns for water conservation, improved management of deep percolation losses and drainage flows, and new approaches to enhance yields has prompted interest in alternative irrigation methods. Drip irrigation of numerous crops is well established and gaining in popularity in many parts of the arid western United States, particularly in high value crops such as many tree and vine crops, tomatoes and many vegetable crops.

Most cost analysis data for irrigation systems evaluate costs of the initial investment, fixed costs, and ongoing variable costs of irrigation systems. Several cost comparisons of drip irrigation versus several gravity-flow or sprinkler irrigation options have been conducted in the past ten years (Wilson *et al.*, 1984; Phene *et al.*, 1993), but in general there are few detailed evaluations that account for the net income differences expected across a wide range of yield potentials, soil conditions, prices and availability of water, energy, labor and other inputs. One of the problems in most of these analyses is that a combination of yield, quality, water conservation, groundwater protection, or associated factors must come together in order to make it profitable for growers to change irrigation systems or management. Under the right combination of conditions, much potential for improvement in water use efficiency can be realized with changes in both irrigation systems and management practices.

Methods and Discussion

Irrigation system and management factors important in determining water use efficiency

Developed water supplies have many potentially competing uses, including agricultural, industrial, municipal, recreational, and wildlife habitat protection and enhancement. In addition, regulations for protection of minimum streamflows and protection of the quality of surface waters and groundwater will play an increasing role in determining acceptable uses and consequences of water use in agriculture. Development of new water storage facilities in many parts of the western U.S. is usually considered too expensive for use in expanding water supplies for agriculture, and often are considered too expensive or unacceptable for environmental reasons even for municipal and industrial supplies. The result is that when perceived inequities in water distribution occur, transfers of existing water supplies from uses such as agriculture to meet other water needs are often viewed now as one of the most cost-effective sources of water. Public and legislative demands for protection of wildlife habitats, river systems, groundwater and surface water quality, and provisions for recreation and open space put additional constraints on water supplies for agriculture.

Concerns regarding low water use efficiency in agriculture are becoming more prominent for a variety of reasons. It can be argued that some portion of surface runoff and deep percolation is not strictly "lost" since much of it can be accounted for as return flows and stored water on a regional basis. This return flow water, however, is generally returned with somewhat degraded water quality, and represents a lost opportunity to make economic use of the water when it was first available on-farm. There are numerous discussions and definitions of on-farm and basin water and irrigation efficiency (Heerman *et al*., 1990) which are beyond the scope of this paper.

Choice of the most suitable irrigation system and management is a complicated decision involving both farm-scale and regional factors. No one system and management will be cost-effective in meeting water conservation, groundwater and surface water protection, yield, and net return goals under all conditions, but there are some general principles which can be discussed.

Irrigation efficiency

Irrigation efficiency (IE) is defined (Heerman *et al.*, 1990) as the ratio of the volume of water which is beneficially used to the volume of water applied. Beneficial uses include crop water use, leaching for salinity control, and water applications for uses such as cooling, frost protection, or chemical applications. Losses to deep percolation, surface runoff, or spray drift and evaporation represent reductions in irrigation efficiency. Water use efficiency (WUE) is usually defined as the ratio of dry matter or harvestable yield per unit of water evapotranspired (Phene *et al.*, 1993). Both are useful terms which together give a measure of efficiencies in applying water and achieving favorable crop responses to evapotranspired water. Improvements in WUE can be approached through: (1) improvements in understanding crop water requirements, critical growth stages important in determining yield potential; (2) irrigation scheduling better matched to crop water requirements, crop rooting depths and soil water storage; and (3) changes in irrigation water delivery and application systems.

Improvements in IE and WUE are a function of ability to match timing of irrigation with plant water needs (considering the ability of the soil to store water within the root zone) and uniformity. The uniformity of water distribution is influenced by proper hardware design to differing degrees across irrigation systems, but is also strongly influenced by management factors and the appropriate match of irrigation management with prevailing soil conditions. With many irrigation systems, the amount of flexibility in managing water is limited. Timing of irrigation and the amount of water applied are not strictly management decisions, and irrigation uniformity is not controlled only by proper design of the hardware used in irrigation. Flexibility in water applications may be controlled at a large scale by water district management or government regulations, or at a field scale by factors such as soil water intake characteristics. Potential for improvements in IE and WUE due to irrigation water management depend on the degree of understanding of the crop and soil system, the flexibility in management offered by the irrigation system and water provider, and the sensitivity of yield-determining factors in providing an economic response to improvements in water management.

Major factors influencing options in improving WUE

The primary systems in use on cotton are gravity-flow methods and sprinkler systems such as center pivots or linear-move sprinklers. Major irrigation systems can be characterized as belonging to three major groups: (1) gravity flow systems such as furrow, border, level basin and variations of these methods; (2) pressurized-flow systems such as all types of sprinkler systems (solid set, center pivot, linear move, sideroll) and microirrigation systems (drip, microspray); and (3) subirrigation systems (drainage-control of groundwater depth). Although 54% of U.S. irrigated acreage was irrigated using gravity flow methods in

1992 (Irrigation Journal, 1994), this was down from 64% of the total area in 1982. Increases in use of sprinkler system such as center pivots account for much of the shift, and much of this was not in cotton production areas. Microirrigation use is increasing, but still represents relatively small areas in many crops and is most widely used on vegetable, tree and vine crops.

Crop characteristics

Characteristics of the cotton crop influence the irrigation system and management options. Whereas many crops are small-seeded and difficult to establish under many soil or environmental conditions, cotton is relatively tolerant of poor seedbed conditions. As a seedling, it is much better suited to survive conditions of low water content or moderate salinity than many other crops (Hoffman, 1981). Cotton can develop a deep root system and utilize considerable stored soil water if soil conditions permit, and most varieties are tolerant of a broad range of water deficits, although some growth and yield losses can be expected if water deficits are severe or of long duration. When considering installation of high capital investment or semi-permanent irrigation systems, it is important to consider what other crops will be grown in rotation with cotton and their compatibility with management practices. An important question from an economic and practical standpoint is whether the crops can be established using the primary irrigation system or whether a secondary system (such as moveable sprinklers) are needed for germination/seedling establishment. In order to justify the expenses and achieve an acceptable economic net return, growers should consider: (1) crop response to improved or alternative irrigation management (ie. can you achieve a significant improvement in yield or quality that will improve net returns?); (2) sensitivity of the crops to the effects of the irrigation systems on aeration/pathogen/insect dynamics; (3) crop sensitivity to salt and toxic element accumulations; (4) compatibility with crop rooting depth; (5) net economic returns possible with the crop rotation.

Site characteristics

The supply characteristics of the irrigation water source are important in determining irrigation system and management options. The water source may be highly-regulated in terms of the discharge volume, schedule of availability during the season, and the duration of availability. Water source flow rates to the farm may be better-suited to high flow rates per unit area/low frequency irrigation or more appropriate for low flow rate/ high frequency pressurized-flow systems. Depending on soil water holding capacity, these factors strongly impact the ability to match water deliveries over time to crop water needs. In order to have the ability to deliver water at high-frequency, pressurized systems will require on-farm water storage facilities or direct access to wells or on-demand water sources.

Water quality characteristics can have a strong impact on suitability of irrigation systems (Hoffman, 1981). Crop sensitivity to foliar exposure to poor quality irrigation water and the suitability and efficiency of irrigation systems in leaching accumulated salts and potentially toxic elements can be significant problems in some irrigated areas. In areas where shallow groundwater is a problem, there is considerable potential for limiting drainage volume through reuse of drainage water or management of the crop to facilitate crop water use from the shallow groundwater. Irrigation systems vary in their suitability for use with water of degraded quality, and use of these waters indefinitely by either reuse or shallow groundwater uptake does come with future problems in eventual requirements for leaching and difficulty in isolating toxic element accumulations from natural water systems and wildlife. Soil water holding capacity, spatial variability in infiltration characteristics, hydraulic properties affecting water and solute flow and physical or chemical characteristics restricting rooting depth can all exert major influences on the choice of suitable irrigation systems.

Topographical characteristics such as the uniformity of grade, slope, and surface features which influence options in irrigation hardware or management are also very important in making irrigation system choices. Field size influences economics in that some systems are impractical or not economically-feasible until a certain size can be accomodated. Irrigation management and systems must be compatible with tillage, chemical application, harvesting operations or current practices must be modified to accomodate new practices. Impact of the alternative irrigation practices on long-term problems such as potential for compaction should be evaluated.

<u>Economics / grower acceptance / regulatory factors</u>

This is a complicated topic which must include consideration of the cost and benefits associated with the factors discusses above. Major factors to be analyzed include the availability and cost of field labor as well as skilled management labor, installation (capital), variable and maintenance costs, expected system longevity, cost of system components and how costs are expected to change over time, cost of energy used in pumping water supplies, pressurizing, and operating the systems, costs of water and other inputs and the dependence of expected yield responses on specialized inputs (i.e. soluble fertilizers used in microirrigation systems, similar inputs), and the availability of repair parts at farm location.

Many changes in irrigation systems come with the perception that crop yield and quality, amounts of water used, or amounts of drainage generated can be significantly improved by changing irrigation systems and management practices. Due to all of the site, crop response, management and economic variables, identifying effects on net returns remains difficult and inexact. Continuing and new studies such as those by Wilson *et al.* (1984), Nef (1988) and Prevatt *et al.* (1992) which evaluate the effects of broad ranges of management, site conditions, and expected crop responses will be needed to assist in identifying cost-effective approaches toward improving WUE while dealing with concerns for water quality and providing water for non-agricultural uses.

California is a good example of a cotton production area where a host of additional factors are and will have an increasing impact on choices of irrigation systems and management. In addition to increasing "competition" for limited water supplies which can become intense during drought years, government regulations at various levels are increasingly being imposed in efforts to protect environmental quality by providing water for fish and wildlife protection under the Endangered Species Act, protecting river systems and estuaries by setting water flow or water quality criteria, and protect surface and groundwater quality by establishing surface and groundwater quality criteria. Soluble nutrients, pesticides, and potentially plant-toxic or animal-toxic materials are of concern, and many research efforts (San Joaquin Valley Drainage Program, 1990) have identified the scope of drainage and groundwater contamination problems in parts of the San Joaquin Valley of California. In areas where these regulatory controls are enacted, these criteria may regulate upper limits on available water, drainage volumes, and groundwater quality. These factors may become the dominant criteria in choosing an irrigation system and management that will meet regulatory criteria, and growers will need to adjust as possible to find an economically-feasible approach to cotton production.

Results

Irrigation systems— imitations and opportunities

Some of the most cost-effective ways to reduce irrigation amounts, affect yield the least, and reduce potential for groundwater contamination may be to reduce preplant or early-season irrigations, use deficit irrigation during certain growth stages if crops yields are insensitive to water deficits or stored soil water can supply water requirements, or allow plants to use shallow groundwater when available. Where appropriate conditions exist and where evidence exists to support the above options, these should be considered in addition to any major changes in irrigation systems.

Sprinkler systems

Types of sprinkler irrigation systems include stationary lateral versus moving lateral systems. Center pivots are used widely in the Texas High Plains areas of cotton production, where they represent a major improvement over gravity-flow systems where topography was often poorly-suited or completely impractical for gravity-flow irrigation. Major improvements in system design and management in recent years have included lower pressure operation, improved sprinkler designs to reduce energy costs and some of the problems with drift and poor uniformity, and alternative tillage to deal with problems of runoff and surface redistribution of applied water resulting from water application rates in center pivots that exceed soil infiltration rates. Center pivots and linear-move systems are also popular in part due to suitability for automated control. Low-energy-precision-application (LEPA) systems have been tested both in Texas and California and have features which can reduce problems with drift, runoff and surface redistribution of water. Research findings with these systems will not be reviewed here. Limited use of center pivots and linear-move sprinklers in California cotton may be related to the perception that basically level topography and land leveling have made gravity-flow systems the appropriate economic choice in most California cotton production areas. Hand-move sprinklers are commonly used for preplant irrigation and germination/seedling establishment irrigations in the San Joaquin Valley, and can provide a means to control applied water more precisely and apply much lower water applications for these irrigations than is possible with gravity-flow irrigation. If growers want the ability to apply water using these approaches or want to take advantage of ability for frequent water applications, energy costs for pressurization and costs of pumps or storage facilities to provide on-demand water must be considered.

Gravity-flow irrigation

Variations on gravity-flow irrigation are too numerous to review here, but include furrow, border-check, level basin, cablegation, surge valve systems, tailwater reuse systems to allow flexibility in advance rates and recycle tailwater, and a variety of automated gates and valves to improve water control (Walker, 1989). Some of the flexibility needed for more efficient surface irrigation lies in the flow rate, flow duration, and flow frequency, which may be under the control of a central water authority instead of the grower. These constraints limit the flexibility of the grower in dealing with the major problems restricting improvements in IE in gravity-flow systems. Uniformity of water applications in most of these systems is lined to advance time and spatial variability in soil infiltration rates (Walker and Skogerboe, 1987; Hanson, 1988). Advance time can be adjusted by reducing run length, increasing furrow inflow rates, compacting furrows to influence infiltration rates, or improving the uniformity of field slope (Hanson, 1988), and in some cases, IE can be further improved through the use of tailwater recovery systems.

The difficulties lie in developing strategies which are compatible with constraints of labor and whole-field operation, since most measures require changes in the duration of irrigation. The combination of changes in inflow rates and set time choices must work with labor availability constraints or some automation method must accomodate the changes. Another problem is that in order to select an appropriate combination of set times and inflow rates that will reduce deep percolation, useable estimates of soil infiltration characteristics are needed. Excessive spatial variability in infiltration rates and within-season changes in soil conditions make this a difficult parameter to accurately assess. Approaches are available to improve gravity-flow irrigation under certain conditions, and additional research and economic analyses are needed to assess the potential for cost-effective improvements in WUE and IE. For maximum flexibility in approaches to improve IE, however, more grower control is needed in modifying flow rates, the availability of water during the season and the duration of available water for each irrigation, and the frequency or available water.

Major advantages of gravity-flow systems are: (1) low direct energy costs for application (although if water is pumped and higher water amounts are used, this advantage may be reduced); (2) many practitioners available who understand basic principles; (3) windy conditions do not influence water distribution; (4) water quality and sediment load in water not a problem in system operation; (5) improvements are available in automated controls of water control structures; and (6) if land is already graded for gravity-flow irrigation, cost for maintenance of grade is generally low. Problems include: (1) the strong influence of soil infiltration characteristics on water distribution and deep percolation; (2) nonuniformity in infiltration can be manifested both spatially and temporally, making it difficult to assess and deal with; (3) usually not suited to frequent, low volume applications (if soil water-holding capacity is low, rooting depths shallow, or crops respond to maintenance of minimal soil water depths, it may be difficult to apply water without excessive deep percolation); (4) field labor requirements can be high relative to other methods; and (5) temporary aeration problems following irrigation more common than with other methods.

Microirrigation

In cotton production, both surface drip and subsurface drip systems can be used in field productions systems. Subsurface drip systems have characteristics similar to those in surface systems, with the added advantage that the laterals are below grade and out of the way of most tillage operations. Also, since the laterals are below the surface, water distribution is not dominated by surface infiltration characteristics. As with sprinkler irrigation systems, if growers want the ability to apply water using these approaches or want to take advantage of ability for frequent water applications, energy costs for pressurization and costs of pumps or storage facilities to provide on-demand water must be considered, although operating pressures and therefore energy costs are generally lower than with many sprinkler systems. Drip irrigation is well-suited to most soil types, although closely-spaced laterals may be required in very coarse-textured soils and that may be cost-prohibitive. These systems can be designed for very high water application uniformity, are well-suited for feedback control using soil, plant or weather station information since they can be operated on a high-frequency basis, can be operated on uneven topography providing pressure compensating emitters are used, and can be used to inject a variety of farm chemicals (nutrients, pesticides). In crops responsive to maintenance of minimum water and nutrient deficits, the irrigation system can be managed for frequent applications in a manner that can't be approximated with other systems.

Limitations or areas of concern not completely resolved include cost of the full system, including installation and maintenance, differences in expected performance problems across the wide range of drip tapes and lines with simple orifices or more complicated emitters, potential for root intrusion, management practices to reduce problems with plugging, identification of most suitable lateral installation depth in subsurface drip systems, and the need for extensive filtration where water quality, sediment loads are a problem. Other concerns which require additional experience and field evaluations to quantify include longevity of the drip system, reliance of expected yield responses on specialized inputs (i.e soluble nutrients) and the impact of changes in input costs, necessity for maintenance of row orientation relative to lateral locations and compatibility with tillage operations, and the need for alternative irrigation systems on an intermittent basis for purposes of leaching or germination and seedling establishment.

The above system characteristics, limitations and options are in no way meant to be all-inclusive, but rather should serve to illustrate the many factors that influence management options and appropriate choices of when to consider changes in irrigation systems. Often, changes in yield potential or water conservation alone will not provide the impetus for major changes in irrigation systems or management, but a combination of factors may provide increases in net returns. Other factors, including regulations concerning competing uses of water and environmental protection, may also force some changes not strictly linked to production economics. Some very limited examples involving drip irrigation in California will be used to illustrate alternative approaches.

Materials and Methods

Subsurface drip evaluations

Cotton was grown in a Panoche clay loam soil at the University of California West Side Research and Extension Center near Five Points, CA in 1991, 1992, and 1993. During the winter of 1990-1991 the field was bedded in 76 cm beds and drip irrigation laterals were shanked in 45 cm deep and 152 cm apart in alternate furrows. The drip line installed was 16 mm-diameter tubing with in-line, turbulent-flow emitters with a nominal flow of 4 L h-1 and a spacing of 0.91 m. Sand media and 200-mesh screen filters were used for water filtration.

Six subsurface drip irrigation treatments were imposed on two Acala types (GC-510, Columnar C2), and one Pima type (Pima S6). The irrigation treatments represent combinations of different water application rates and different timing of periods of deficit irrigation during the growing season. Grass reference evapotranspiration (ET_o) was determined using a large weighing lysimeter planted with a cool-season blend of grasses. Estimated crop evapotranspiration (ET_c) was calculated by multiplying ET_o by a locally-derived crop coefficient (Davis et al, 1982). During the 1991 and 1992 seasons, average irrigation water salinity (EC_w) ranged from 0.84 to 1.15 dS m^{-1}, with Boron levels of 0.7 to 1.0 mg B kg^{-1}. Water of lower salinity (0.5 to 0.6 dS m^{-1}) was used in the 1993 season.

Each field plot was ten 0.76 m rows wide by 28 m in length. Three replicates of each treatment were arranged in a randomized complete block design. In addition, each plot was split into two PIX (mepiquat chloride) treatments (5 rows each): (1) a control (no PIX); and (2) one application of 0.5 pt (1991, 1992) or 0.6 pt (1993) PIX ac-1 during early bloom.

Cotton was planted on day 98 (1991), day 97 (1992), and day 109 (1993) and one 27 m row was harvested per plot on day 294 (1991), 301 (1992), and 314 (1993) using a single-row spindle picker. Sprinkler applications (both pre-plant and for germination) totalled 142 mm in 1991, 151 mm (1992), and 126 mm (1993). Approximately 168 mm of rain fell from December 1990 to March 1991, 195 mm from December 1991 to March 1992, and 211 mm from December 1992 through March 1993. A flow-sensing proportioning pump was used to continuously inject liquid fertilizer into the drip system. Nitrogen was applied as calcium-ammonium nitrate during June and July of both years, and potassium nitrate was used as the N and K source during August. These nutrient sources were used to apply a higher N-content material (calcium-ammonium nitrate) during the peak N demand period (early- to mid-season) and a lower N-content material and supplemental K during the high K uptake period (mid- to late-season). Phosphoric acid was injected to provide phosphorus. Total N, P, and K applications were similar across the three years of the study, with 212, 83, and 111 kg ha^{-1}, respectively, in 1991, 203, 84, and 126 kg ha^{-1} in 1992, and 205, 87, and 130 kg ha^{-1}, respectively, in 1993.

Soil water content was monitored to a depth of 3.1 m by neutron attenuation at intervals throughout each season. Actual crop evapotranspiration was calculated as applied water plus rainfall plus soil water depletion, assuming negligible deep percolation. Soil samples were collected in 15 cm increments to a depth of 60 cm and 30 cm increments to 270 cm to allow analysis of seasonal changes in nutrient status and salt accumulation.

Early to mid-season leaf water potentials (LWP) were determined using a Schollander-type pressure chamber. Three subsamples per field replicate were evaluated for each treatment. Fully-illuminated, recently-mature leaves from the fourth or fifth most recent main stem node were collected in mid-afternoon (1300 to 1500 hours PDT), placed in a plastic bag while still on the plant, excised, and stored temporarily in humid, sealed plastic containers. LWP's were determined within 10 to 15 minutes following collection.

Results

Subsurface drip field study

<u>Applied water, soil water use, plant water status, ET_c</u>

Extensive, deep root system development and high soil water holding capacity allowed use of large quantities of stored soil water. Average beginning-of-season stored soil water (within 30 days after planting) in a 3 m profile averaged 845, 820, and 750 mm in 1991, 1992, and 1993 respectively, while end-of-season (within 20 days after defoliation) average stored soil water averaged 590, 495, and 435 mm in the same three years, respectively. The three years were somewhat different in monthly heat unit and ET values, with a cooler early season in 1991 and 1992, but a hotter, higher ET late season in 1991 than in other years.

Calculated whole-season ET_c in 1991 ranged from a low of 538 mm in treatment T4 (Pima) to a high of 749 mm in treatment T3 (Columnar). In general, ET_c of the Pima was lower than in the Acala due to lower soil water depletion. Extensive use of stored soil water resulted in relatively high ET_c values even in the 60% and 80% ET_c treatments. In 1992, total season ET_c ranged from 590 to 882 mm. One cause of higher drip water applications in 1992 was that 80 to 100 mm of water applied through the drip system from day 148 to 178 was in excess of ET_c in order to replenish soil water depleted during 1991. Extensive stored soil water use in all irrigation treatments and varieties resulted in similar ET_c values within treatments in Acala and Pima varieties in 1993 and a tighter range of estimated ET_c across varieties than in the other two years.

Soil water storage and use of stored soil water was much higher during the late August through September period of 1992 and 1993 than it was during the same period in 1991. Since data indicates all treatments went into vegetative cutout prior to day 225 in all three years, there may be a significant opportunity to reduce ET_c by 50 to 100 mm if the drip irrigation could be terminated 15 to 20 days earlier.

Within any measured irrigation treatment, few significant differences in mid-afternoon leaf water potential (LWP) existed between the Columnar and GC510 varieties. Water deficits were mild in the 100% ET_c (T1) treatment, with even the -1.5 MPa LWP corresponding with a crop water stress index value less than 0.1. In contrast, the LWP in the treatments receiving the least water (T5, T6) declined to -1.7 MPa by day 200 and to less than -2.0 MPa by day 215, with even more severe late season reductions in LWP in 1992 and 1993.

Since the drip system applied water multiple times per day but in deficit amounts, stress developed gradually and plants typically extracted a minimum of 200 mm, and in many cases, in excess of 300 mm of stored soil water to supplement applied water. LWP differences were largest during the boll-filling period, when available stored soil water had been depleted in much of the soil profile in low water treatments.

Growth components and lint yield

Cotton ET_c generally was highest in treatment T1 and lowest in T6. Most growth parameters measured during July and August of both years reflected these treatment differences, with reduced plant heights, slight reductions in main stem nodes, lower leaf area, and lower total dry matter in the more severely water-stressed treatments (treatments T5, T6). During both years, data on node number, plant height, and nodes above white flower indicated that vegetative cutout occurred during the first or second week of August.

In most treatments, the 1991 and 1993 cotton set bolls earlier, produced bolls lower on the plant, and had lower leaf area to boll number or boll dry weight ratios than cotton treatments in 1992. The more severe water deficits in treatments T4, T5, T6 produced plants with leaf areas, height and above-ground dry matter that in mid-August averaged 8 to 14% lower than in higher water application treatments.

Pima lint yields ranged from about 1900 to 2300 kg ha-1 with an average of 2098 kg ha^{-1}; GC-510 ranged from 2100 to 2700 kg ha-1 with an average of 2440 kg ha^{-1}, and Columnar ranged from 2200 to 2400 kg ha^{-1} with an average of 2298 kg ha^{-1}. The variety GC-510 exhibited a trend toward a positive relationship between increasing lint yields and ET_c, while no significant relationship existed for the Columnar or Pima cottons. Similar relationships were observed under both PIX treatments within each variety.

Turnout data to determine lint yields for the 1993 season were not available, but seed cotton yields across all irrigation and PIX treatments averaged about 70% to 76% average yields from 1991 and 1992. Differences across irrigation treatments followed the same general trends identified in the two prior years.

Further improvements in water and nutrient use efficiency in producing high cotton yields under subsurface drip irrigation may require continuing refinement of fertilizer and water management as new varieties become available.

Discussion

The subsurface drip irrigation experiments at the West Side Research and Extension Center demonstrate that the potential exists to achieve high lint cotton yields with relatively low ET_c and essentially no deep percolation. Water use efficiencies in these experiments approach 3.5 kg lint/ha/mm ET_C, which is extremely high compared to most cotton production in California's San Joaquin Valley.

There are a number of economic analyses, larger-scale demonstrations and field research projects which provide some comparisons of yields, water use, and net economic returns of cotton grown under a range of irrigated conditions in California and Arizona.

An economic analysis of potential for surface drip irrigation in Arizona (Wilson *et al.*, 1984) concluded that the costs in operating a drip system on cotton were comparable to those under conventional furrow irrigation. They based their analyses on early research which suggested that water savings of up to 40% could be realized in some areas by switching to drip irrigation from conventional furrow irrigation, with at least a 250 kg/ha increase in yields in most soils. Increases in net economic returns under drip irrigation were linked strongly to expected yield increases. Without yield increases, the systems were not profitable under many soil and management conditions. Highest profitability was expected under conditions of medium to coarse-texture soils and high evaporative demand conditions. Their analysis stressed the need for more research data to verify potential for water savings and improvements in yield with drip irrigation.

Cotton yields and applied water in Arizona under furrow, center pivot sprinkler and subsurface drip irrigation were compared on a commercial farm (not a research experiment) and reported by Wuertz and Tollefson (1992). Using averages determined over nine to eleven year periods, lint cotton yields averaged 1512, 1344, and 2117 kg/ha in furrow, sprinkler and subsurface drip fields, respectively, with 1651, 1067 and 813 mm average water applications, respectively. This resulted in WUE values ranging from 0.9 kg/ha/mm in the furrow plots, to 1.26 kg/ha/mm in sprinkler fields, to a high of 2.60 kg/ha/mm in the drip fields. Under conditions in Arizona, they reported the highest net economic returns in the drip-irrigated fields.

A large-scale irrigation project was conducted near Coalinga, CA in the San Joaquin Valley of California (Phene *et al.*, 1993b). Four irrigation methods were evaluated on 16.2 ha sites: (1) LEPA (low energy precision application linear-move sprinkler system; (2) historic furrow (irrigation scheduling as determined by grower, with 400 m run lengths); improved furrow (with 200 m run lengths and a tailwater recovery and reuse system); and a subsurface drip irrigation system installed at 40 to 45 cm depth and 2 m lateral spacing. All fields were underlain with shallow (0.9 to 1.4 m deep, depending on time of season and plot), saline groundwater of a quality that could be used by cotton to meet water needs. Cotton was grown during the 1989, 1990, 1992 and 1993 seasons, with planting typically in early April. Due to operational problems with the LEPA system, irrigations were inadequate and poorly timed, resulting in low yields. Performance and net returns of the LEPA system could not be fairly represented in this study. Drip and furrow systems were operated as intended, and comparisons were judged to be reasonable. All plots received deficit irrigation which resulted in uptake from the groundwater. Reductions in preplant irrigation amounts were effective in limiting early-season deep percolation. Irrigation amounts in the drip and historic furrow plots were consistently lower than in the historic furrow plots. The study concluded that acceptable net economic returns could be achieved with the drip system, but depended on increases in lint yields. Lint yields with the subsurface drip system averaged about 1450 kg/ha, versus less than 1200 kg/ha in the furrow systems. Average net economic returns per year were highest in the drip-irrigated plots, at $267 (U.S.) per acre, compared with $204 and $238 per acre in improved furrow and historic furrow plots.

Another experiment on coarse-textured soils near Shafter, CA reported by Detar *et al.* (1992) compared seasonal water use and yield responses of Acala cotton under furrow and subsurface drip irrigation. Comparisons were conducted both in plots with a relatively uniform, sandy loam soil with relatively uniform surface infiltration and physical characteristics (for comparison purposes, identified as a "good" soil) and in a "poor" soil with highly variable texture and infiltration and a clay layer at 1.25 m depth. Furrow fields had a tailwater recovery system and net applied water was calculated as total applied minus runoff to the tailwater system. During a four year experiment, yields were not significantly different between furrow and drip-irrigated plants in the "good" soil plots, yielding in excess of 1800 kg lint/ha. In the "poor" soil, the drip plots averaged about 250 kg/ha higher lint yields than in the furrow-irrigated plots. Total water applied was much lower in the drip plots, averaging

109 cm (furrow) versus 65 cm (drip) in the "good" soil area and 121 cm (furrow) versus 66 cm (drip) in the "poor" soil area.

Results from these experiments demonstrate that the potential for yield improvements and savings in water applications is achievable under certain conditions. Irrigation systems and management are needed which have improved abilities to conserve and make best use of water, particularly when availability, cost or regulations restrict supplies. In crops which are responsive to water and nutrient stress, improved systems and management should supply water and nutrients for improvements in economic responses in yield and quality. If the potential for yield responses is not likely or the cost of water, energy and other inputs remain low, some irrigation options will not be economically feasible. It is possible to modify systems and management practices to both more precisely meet crop water requirements and minimize deep percolation and drainage, provided there is economic incentive or regulatory controls to encourage these improvements.

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