Irrig Sci (1993) 14: 53-63

Irrigation Science

Engineering systems to enhance irrigation performance

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Received: 25 October 1992

Abstract. The desirable irrigation system applies water at a rate that allows all water to infiltrate and distributes the water in space and time to match crop requirements in each parcel of the field. Various types of irrigation systems and management strategies have been developed in attempts to achieve the "desired" system. Our objective is to review various methods of enhancing irrigation performance. Although the "desired" system has not been attained, considerable improvements have been made based upon selection and management technologies which generate profits within the constraints of environmental prudence. Each irrigation system has inherent opportunities for enhancing irrigation performance. Likewise, each has limitations in achieving maximum crop productivity per unit of applied water. Methods to improve the performance or surface irrigation can be grouped into those that increase the uniformity of water intake, reduce runoff losses, or decrease spatial variability. Two surface irrigation systems that enhance performance are surge-flow and level-basin. The uniformity and efficiency of sprinkler systems can be enhanced by computer-based design procedures and, in some cases, by applying low-energy, precision application concepts. Advantages of microirrigation are less surface area wetted, which minimizes evaporation and weed growth, and improved application uniformity which is specifically designed into the distribution network. An appropriate management strategy is necessary to attain the potential of an irrigation system engineered to match crop water requirements, and soil and environmental conditions. The best irrigation method applies the amount of water desired at the appropriate time while providing for leaching requirements, agronomic operations, and environmental considerations. With enhanced engineering and computer capabilities and improved knowledge of the soil-plant-water continuum, irrigators will adopt "prescription" irrigation. Prescription systems apply precisely the prescribed amounts of water, nutrients, and pesticides to match the production capacity of each parcel of land.

Water-use efficiency (amount of marketable product per unit of water consumed) is inherently tied to the economics of an irrigation enterprise. Increasing efficiency reduces annual operating costs and increases the marginal net benefit of irrigation. Perhaps more importantly, as competition for water supplies increases, water-use efficiency will dictate the sustainability of the enterprise. Improving water-use efficiency increases the opportunity cost of water which encourages conservation and enhances sustainability. With today's economy, the payback on the investment to improve performance must consider sustainability not just amortized costs. Thus, the objective of maximum economic efficiency is inseparable from maximum water-use efficiency. With this premise, this review will focus on enhancing water-use efficiency through improved performance of irrigation systems.

Desirable irrigation systems apply water in a timely manner, at a rate appropriate for soil conditions, and in an amount consistent with crop productivity and water quality goals. Numerous types of irrigation systems and management strategies have been developed to achieve a "desired" system. Each scenario of irrigation system, soil, and crop provides a different potential of application efficiency and uniformity. Achieving the desired performance depends on selecting designs and managing technologies to generate profits while meeting environmental and resource utilization constraints. Ultimately, costs for water, application system, conveyance, pressurization, drainage, environmental protection, and management must be charged against yield revenue.

Historically, irrigation water was applied to small fields by gravity with the timing and amount often dictated by circumstances rather than crop needs. Copious amounts of water were generally applied to minimize the risk of water deficiency. Later, diversions, reservoirs, canals, and various types of surface irrigation systems were developed to enhance water management. As competition for water increased, engineering and management schemes were developed to apply water more uniformly and efficiently. The goal to achieve uniformity was driven by well-documented evidence that nonuniform applica-

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tions lead to surface runoff and excessive deep percolation because irrigators normally tried to irrigate fully every parcel in the field. Striving to improve uniformity has resulted in improved surface, sprinkler, and microirrigation systems.

Now, with enhanced engineering and computer capabilities and improved knowledge of the soil-plant-water continuum, we can improve upon the uniform application of water with "prescription irrigation." Because soil, topography, micro-environment, nutrient status, groundwater conditions, and other factors that impact crop yield vary throughout many fields, the most desirable irrigation system should not apply water and associated materials uniformly throughout the field. In fact, the desirable system should apply precisely the prescribed amounts depending upon the production capacity of each parcel. This desired system can be termed "prescription irrigation." To use resources effectively, we must know the ability and/or requirements for each parcel (an area as small as 0.1 ha) and then apply precisely the required inputs of water, nutrients, and pesticides at the optimal time to satisfy the production capability of each parcel. The design must facilitate a dynamic distribution system that allows varying ratios of water application to parcels throughout the season.

Today, there are four general types of irrigation systems: surface, sprinkler, microirrigation, and subirrigation. Each system has inherent opportunities for enhanced irrigation performance and limitations to achieving the maximum water-use efficiency. Irrigation efficiency (e_i) here will refer to the ratio of the volume of water which is used beneficially (V_b) to the volume of irrigation water applied (V_a) (ASCE 1978). Beneficial uses include crop evapotranspiration, salt leaching, frost protection, crop cooling, and pesticide or fertilizer applications. Applied water that goes to deep percolation in excess of salt leaching requirements, surface runoff, wind drift, spray evaporation, weeds, and canal conveyance or operation losses is not beneficial and decreases irrigation efficiency. Methods to improve the performance of surface irrigation can be grouped into those that increase the uniformity of infiltration, reduce runoff losses, decrease spatial variability, and improve the control of applications. The uniformity and efficiency of sprinkler systems can be enhanced by improved system design and management to match water application with soil water deficits. Properly designed microirrigation systems can decrease the surface area wetted to minimize evaporation and weed growth and still match applications with water deficits. Sub-irrigation is accomplished by raising the water table so that capillary action will move water upward into the soil root zone. It can only be practiced where underlying formations allow the maintenance of a shallow water table, ample water is available, and salinity is not a hazard.

An appropriate management strategy must be developed in concert with the design of the selected irrigation system. The best method of applying the desired amount of water at the appropriate time, while providing for leaching requirements, agronomic operations, and environmental considerations, can only be selected when all the requirements are understood and techniques and equipment have been developed to satisfy the demands placed upon the system. Proper management must then be employed to achieve the potential of the selected irrigation method. Design defines the ultimate potential and management dictates the actual level achieved. The achieved level is often well below the ultimate potential.

The objective of this review is to highlight recent advances in irrigation design and management that appear particularly promising or have been field demonstrated. Many of the advances described are directed toward enhancing the uniformity of water applications. A few examples of engineering systems for prescription irrigation are also given on the premise envisioned that future advances in irrigation will focus on prescription application.

Surface irrigation

Surface systems are the oldest and most common method of the four general types of irrigation systems. Despite their performance limitations, surface systems account for about 90% of the irrigated area of the world and will continue to be a major system worldwide for the foreseeable future. However, there are inherent problems in achieving high performance. The time available for water to enter the soil can be significantly different across the field and infiltration is neither uniform in space not constant in time. Surface soil conditions are extremely dynamic and influence application efficiency and uniformity. The conveyance systems for surface irrigation are frequently inefficient and are sometimes managed without regard to crop water needs, leading to reduced productivity and/or drainage problems. In addition, many surface systems are labor intensive. Even with these many limitations, continued improvement of surface systems and their management is essential to enhance performance because more efficient systems are not economically justifiable in many instances.

Two surface irrigation systems, "level basin" and "surge-flow", have been developed recently to improve uniformity by equalizing the opportunity for water to infiltrate throughout the field. These systems are described briefly and their expected performance is discussed.

Surge-flow irrigation

The intermittent application of water, to furrows or borders in a series of relatively short on and off time periods is referred to as surge-flow irrigation. Surge-flow irrigation can be used as originally envisioned (Stringham and Keller 1979) to achieve cutback stream sizes to reduce runoff; however, it is more commonly used now as a management tool to improve performance, versatility, and efficiency (Humpherys 1989). The most common surge-flow system consists of a split-set layout with a valve installed in a tee configuration at the center of a gated pipeline. Water is supplied from the mainline to the base of the tee. A baffle in the valve diverts the flow

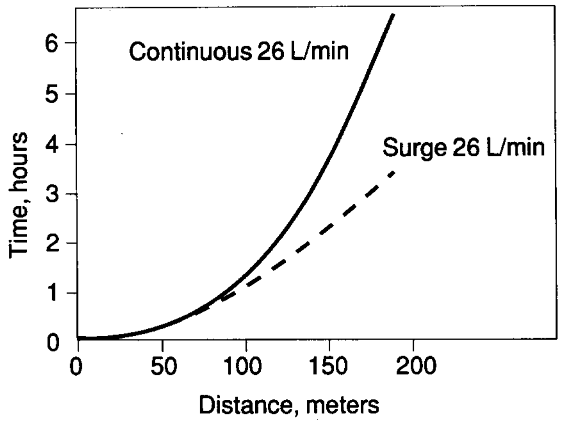

Fig. 1. Advance curves for surge and continuous furrow streams on a silt loam soil near Kimberly, Idaho. Cumulative time for surge streams is the elapsed time minus the off-time (adapted from Humpherys 1989)

alternately to blocks of furrows of equal size on each side of the valve. Each subsequent irrigation set uses a different block of furrows on each side of the valve. The gates in the pipeline are opened and closed manually or automatically for each irrigation set. Valves are available with controllers that have various features and degrees of sophistication including solar battery-charging options and computing capability with fixed and variable algorithms. Most valves can be programmed for a reduction in flow rate (cutback) by decreasing the on/off time.

Surge-flow irrigation generally reduces the soil's infiltration rate which hastens the stream advance down the furrow thereby enhancing distribution uniformity. The improved distribution uniformity of surged furrows compared to continuous flow is illustrated in Fig. 1. The primary mechanisms noted for more rapid advance are soil consolidation due to negative hydraulic gradients that develop in the soil water during flow interruption and surface sealing caused by soil particle migration, reorientation, and deposition. Surge-flow irrigation normally has its greatest impact during the season's first irrigation or following tillage. As the soil consolidates during subsequent irrigations or due to rainfall, the positive impact of surge-flow decreases. Surge-flow has caused greater reductions in infiltration on course-textured soils than with fine-textured soils (Testezlaf et al. 1987; Walker et al. 1982). Very-fine-textured soils have shown little or no response to surge-flow (Bautista and Wallender 1985; Manges et al. 1985; Pitts and Ferguson 1985).

Field experience with surge-flow on a variety of soils has shown that a given flow rate will often advance to the end of the field in about the same elapsed time as for continuous flow. Thus with a cycle ratio of 0.5 for the two blocks of furrows, twice as many furrows can be wetted with approximately the same total volume of water and the same elapsed time as for continuous irrigation. Using variable cycle times, Bishop et al. (1981) found the advance time for non-wheel track furrows on a silt loam soil could be three to four times faster than for continuous flow. Goldhamer et al. (1986) reported the average advance volume ratio (surge to continuous) to be 0.6 for sandy loam, clay loam, and silty clay soils with surge increasing the average distribution uniformity by 15 to 40% depending on soil type. This resulted in a 60 to 80% reduction in deep percolation. In Colorado, Israeli (1988) reported an irrigation application efficiency of 85% for surge-flow compared to 55% for continuous irrigation.

Level-basin

The surface application of a controlled amount of water over a level soil surface, generally over a short period of time, is termed level-basin irrigation. The basin, surrounded by a dike, may be of any configuration. The primary difference between level-basin and traditional surface methods is that the irrigation water is applied rapidly such that the preponderance of infiltration occurs after the water has covered the entire basin. In the southwestern United States about 400,000 ha have been converted to level-basin irrigation during the past 30 years (Dedrick 1990). Commercial systems are usually associated with large flow deliveries from various types of open channels. Level basins are one of the techniques being adopted in the Central Arizona Project to improve water-use efficiency (Arizona Department of Water Resources 1988).

Like all irrigation methods, level-basins have advantages and limitations. Advantages include the potential for high distribution uniformity, high efficiency, uniform salt leaching, minimal deep percolation, no runoff, and reduced labor requirements. Limitations include the impact of soil texture on infiltration (level basins are best suited to soils having medium to low infiltration rates), economic concern when used on steep natural slopes (high leveling costs, exposure of less productive subsurface soils, or very small basins), requirement for precisely leveled soil surface, excess water from precipitation and/or irrigation, delivery capacity per unit area must be high, and delivery capability (irrigator must be able to get water on demand, minimum requirement is to be able to irrigate on a flexible schedule). Sizing the basins is the major design objective so that the desired distribution uniformity is met for the design depth of application. A computer solution of the design procedure is available (Dedrick 1990). Conveyance and control structures along with erosion protection facilities may need to be upgraded for existing supply systems.

Sprinkler irrigation

Sprinkler systems are classified by how the pipe distribution systems operate. The three major types are: systems that remain stationary, systems that are moved periodically, and systems that move automatically while applying water. The pressure required to distribute the applied water and operate the sprinkle applicators is usually provided by pumps. Fixed sprinkler systems only need to be cycled on and off to apply water under pressure. Some fixed systems are moved into and out of the field to permit agronomic operations. Periodically moved systems like the side roll, are similar to fixed systems but the system is too small to irrigate the entire field at once and must be moved progressively across the field. The traveling sprinkler, frequently called a big gun, consists of one large capacity sprinkler mounted on a self-propelled chassis. The sprinkler travels in a straight line while being supplied water through a flexible hose or an open ditch. The traveling system that has one end of the lateral pipeline fixed with the lateral rotating about the pivot point to irrigate a large circular area is called a center pivot system. Lateral-move systems combine the structure and guidance features of a center pivot with a water delivery similar to that of a traveling sprinkler.

The sprinkler innovations discussed here are to highlight prescription irrigation techniques and new designs to enhance uniformity. The design and management of a center pivot to incorporate geographical information system technology and the performance of the low-pressure, precision-application (LEPA) concept are summarized.

Center pivot design

As with other management and design decisions, economical and environmental issues determine sprinkler system selection. For example, the selection of a sprinkler system that operates at low pressure decreases pumping cost for a given water volume but it may increase surface-water runoff. If runoff is excessive, savings from low pressure may be offset by the increased volume pumped to compensate for decreased irrigation efficiency. In addition, the increased runoff may well have negative environmental impacts.

Computer-based design procedures have been developed to match the sprinkler irrigation system with soils, crops, and topography to enhance performance. With the computer-design procedure, several design alternatives can be analyzed simultaneously to assess which is most appropriate based upon water conservation, energy cost, and system performance. As an example, Wilmes et al. (in press) developed a decision-support system to compare sprinkler systems for fields having non-homogeneous soils. The field soils are digitized into the computer database by overlaying a grid of uniform size squares on the soil survey map and storing a code in the database for the predominant soil in each grid cell. A typical square grid cell has dimensions of 80 m. Soil characteristics stored in the database are mapping unit, slope, available water capacity, irrigation design group (SCS 1979) and soil intake family (SCS 1979). An example of high-pressure and low-pressure impact sprinkler designs are compared in Table 1. The design variables taken as the same for both systems are: galvanized steel mainline pipe of 168 mm diameter, a net application capacity of 6.3 mm/day, a gross system capacity of 47 L/s, a revolution period of 96 hours, and an application depth of 30 mm with an 80% application efficiency. A 50% allowable depletion of soil moisture and a crop rooting depth of 1.2 m were assumed. An annual application depth of 375 mm with a lift of 50 m for an electrical system was assumed for energy requirement comparisons.

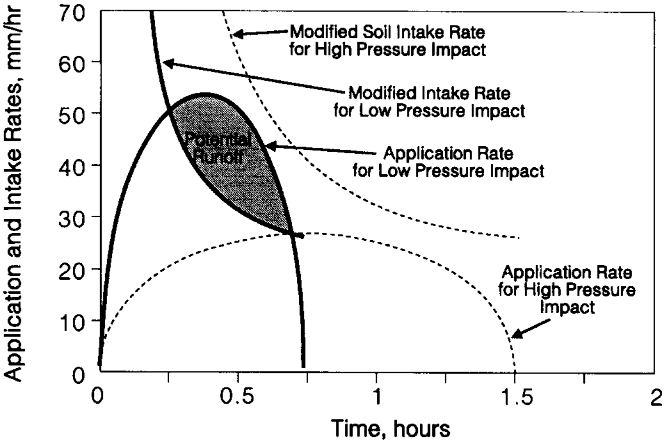

Fig. 2. Application rate, soil intake rate, and potential runoff for two example center pivot sprinkler packages

Table 1. Performance specifications for comparison of high and low pressure sprinkler systems (adapted from Wilmes et al. in press)

Performance specifications	Units	Sprinkler system	
		High pressure	Low pressure
Sprinkler spacing	m	6.1	1.8
Pressure at pivot	kPa	480	205
Pressure at end of mainline	kPa	420	145
Annual energy cost*	$	6 375	4 550

* Energy costs were assumed to be $0.08/kWh

Relationships between sprinkler application rates and soil intake rates are presented in Fig. 2 for the two designs. The soil intake rates have been modified to account for nonsurface saturated conditions (Gilley 1984). The modified intake rates are different for the two sprinkler systems because of differences in peak application rates and the time required for the surface soil to reach saturation. The high-pressure impact sprinklers have a larger wetted diameter leading to a lower application rate over a longer application time period than for the low-pressure impact system (Fig. 2). For the example shown, the soil intake rate exceeds the application rate of the high-pressure system throughout the entire wetting period, thus the entire amount applied infiltrates into the soil and no runoff occurs. During the low-pressure wetting period, the application rate exceeds the soil intake rate for about one-half of the period. The shaded area in Fig. 2 between the application rate and the intake rate integrated over that time period is the potential amount of runoff. Actual runoff is the potential runoff minus the amount of applied water that is stored on the soil surface. Surface storage, of course, is a function of topography and the roughness of the soil surface. The challenge is to design a system such that potential runoff is less than the amount of surface storage while minimizing energy requirements for pressurization.

In Fig. 3, the potential runoff by individual cell is illustrated for the design program of Wilmes et al. (in press). The predicted runoff for the field from an application of

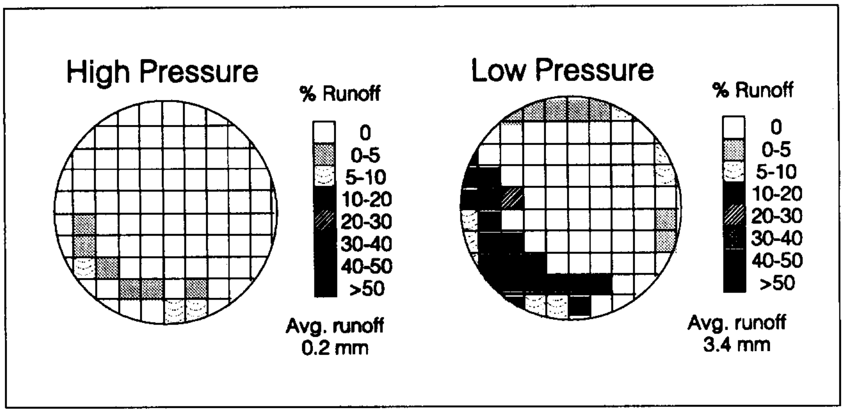

Fig. 3. Spatial runoff distribution for high pressure and low pressure systems depicted in Fig. 2. (Adapted from Wilmes et al. in press)

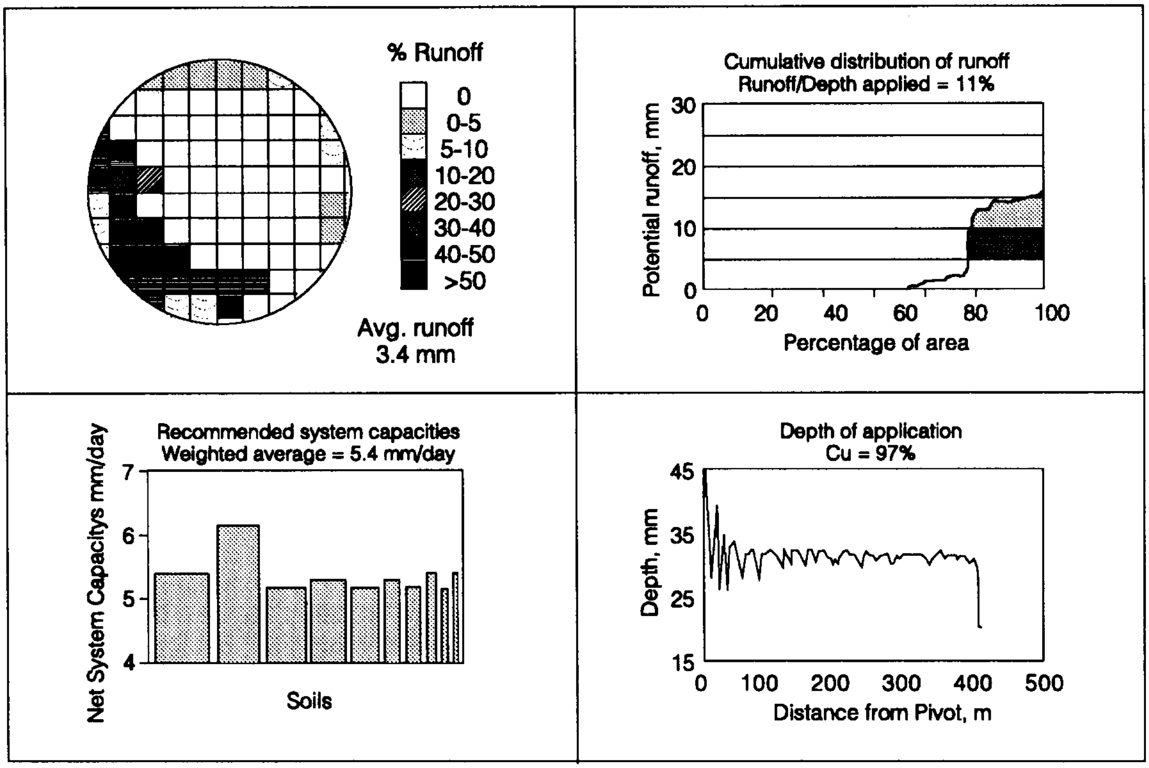

Fig. 4. Results of various analyses for the low pressure system. (Adapted from Wilmes et al. in press)

30 mm is 3.4 mm for the low pressure system and 0.2 mm for the high pressure. In addition to the runoff prediction, several other analyses can be performed in the design program to analyze system alternatives (Fig. 4).

LEPA

A sprinkler irrigation system having potential for high application efficiency is the low-energy, precision-application (LEPA) concept developed for center pivot and lateral-move irrigation systems. In contrast to above-canopy sprinklers, the LEPA system consists of drops from the mainline pipe to spray devices suspended below the crop canopy. Crop rows are planted in a pattern so that the spray device always remains between crop rows. Special tillage or small in-row surface storage basins are generally necessary to store water on the soil surface until infiltration is completed.

One goal of the LEPA concept is to minimize evaporation and drift losses. A second goal is a system compatible with micro-basin land preparation or furrow diking to prevent runoff and to maximize the infiltration of rainfall and irrigation water (Gerard 1987). Lyle and Bordovsky (1981) conducted the first LEPA studies near Lubbock, Texas with orifice-controlled nozzles to discharge water at low velocities in a bubble pattern. In subsequent field trials, it was shown that LEPA heads could be placed in every other furrow without yield loss (Fipps and New 1990). Some LEPA heads are now designed to operate in the three modes illustrated in Fig. 5. By adjusting the nozzle, pre-plant and germination irrigations can be applied in the spray mode. The bubbler mode, used during most of the growing season, is converted to the chemiga-

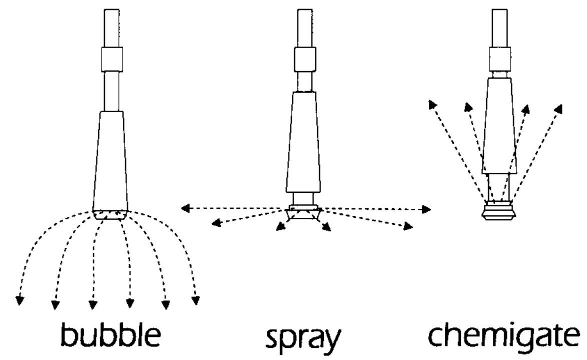

Fig. 5. Three operation modes of commercial multi-functional LEPA heads. (Adapted from Fipps and New 1990)

Table 2. Yield comparisons between conventionally equipped and LEPA converted spans on the same center pivot (adapted from Fipps and New 1990)

Crop	Year	Yield Mg/ha		Increased revenue $/ha
		LEPA	Conventional	
Corn (silage)	1986	62.8	56.0	102
Corn (blue)	1989	2.1	2.0	134
Cotton	1989	0.9	0.8	–
Peas	1989	1.4	1.2	104
Peanuts (Pronto)	1985	5.3	5.0	129
Peanuts (McRan)	1985	4.8	4.2	285
Peanuts	1986	3.8	3.6	502
Peanuts (GK-7)	1989	7.2	6.8	297
Peanuts (florunner)	1989	7.3	6.7	438
Peanuts (florunner)	1989	4.1	3.7	374

tion mode for applying pesticides, nutrients, and defoliants. The multifunctional LEPA heads are located 20 to 45 cm above the ground for optimum performance (Fipps and New 1990). A pressure regulator is frequently a component of the multifunctional head. LEPA systems operated at low pressures, typically 80 kPa or more at the end of the pivot to ensure that pressure regulators along the lateral provide 40 kPa, may offer significant energy savings compared to conventionally equipped sprinkler systems. The LEPA system can achieve an application efficiency in the bubble mode of 95 to 98% (Lyle and Bordovsky 1983), which can save water or increase yield.

Fipps and New (1990) converted a span midway along center-pivot laterals to LEPA and compared performance with an adjacent conventional span. Results over a 5-year period presented in Table 2 show consistently higher yields with LEPA. Where irrigation water is limited, LEPA produces higher yields because a greater portion of the applied water is used by the crop. When water was not limiting, similar yields were obtained with 20 to 30% less water applied with the LEPA system compared to conventionally equipped center pivots.

Water from LEPA systems is discharged onto a small soil area which results in a small wetted diameter and a very high application rate. Adjustments are required to store water on the soil surface to provide enough opportunity time for the water to infiltrate. Runoff will likely occur unless furrow dikes, furrow ripping, deep soil chiseling, or other tillage or crop residue practices are performed to create surface storage or improve infiltration rates. Furrow dikes, mounds of soil placed at intervals across the furrow between beds to form micro-basins for water storage, are frequently used to store surface water. A second method of creating storage is to punch small reservoirs into the furrow using an implement called the dammer-diker. Crops should be planted in a circle for center pivot irrigation so that spray devices remain below the crop canopy. When crossing rows the devices usually ride up in the canopy increasing evaporation from the wetted foliage. Circular planting also prevents the pivot from dumping all the water in a few furrows as when the pivot lateral is parallel with straight rows.

LEPA systems have worked well on flat slopes and cohesive soils where ample storage is provided to prevent runoff. On soils with slopes ranging from 0.2% to 3%, runoff can exceed 40% of the applied depth in some cases. While special tillage helps store potential runoff, the effectiveness of the basins and dikes decreases throughout the season. Usually smaller applications with high frequency irrigation may be needed to manage LEPA systems on slopes. The key to success is maintaining the basins or dikes. If irrigation or rain erodes the basins or dikes the specialized tillage can actually cause more runoff than conventional tillage. Thus, as with any irrigation system, achieving the potential efficiency requires appropriate design and responsive management.

Microirrigation

The term "microirrigation" is typically applied to several low pressure systems, including drip/trickle, subsurface drip, bubbler, and miniature spray. Microirrigation systems are characterized by their distribution of water in closely spaced, pressurized conduits that apply water frequently and at low rates on or beneath the soil surface. Trickle irrigation is the most common microirrigation system. It is best suited for widely-spaced perennial crops or high value row crops. When the tubing and emitters are placed below the soil surface, the system is called a subsurface microirrigation system. Subsurface microirrigation is not the same as subirrigation where the root zone is irrigated by water table control. A bubbler system discharges small streams of water to form pools on the soil surface, usually around trees. The discharge rates of bubblers are higher than drip emitters and usually exceed the soil's infiltration rate; thus, small basins are formed to retain the water where applied. Miniature sprinklers apply water as a small spray or mist. The water delivery system is similar to that for trickle.

Surface drip and miniature sprinkler systems are common microirrigation systems. Subsurface microirrigation is perhaps less common but has distinct advantages in many cases if the high level of design, management, and maintenance are warranted based upon the desired irrigation objectives. The following discussion is centered on subsurface microirrigation but the advantages discussed, except, of course, those derived from being buried, are applicable to the other types of microirrigation.

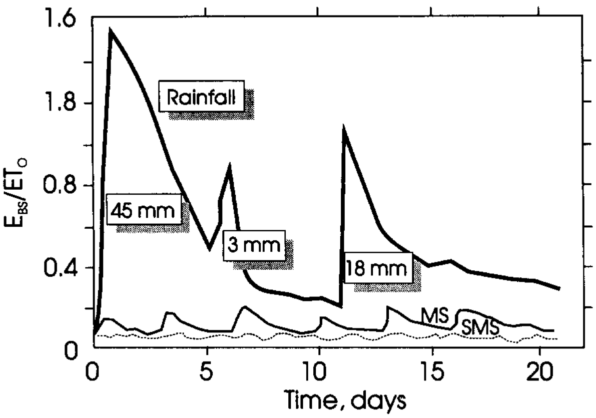

Fig. 6. Evaporation from a bare soil when a microirrigation system is placed on the soil surface (MS) or at a soil depth of 45 cm (SMS) and from three rainfall events. Results are presented as a ratio of bare-soil evaporation (E_{BS}) to reference evapotranspiration (ET_0) of a short-clipped, cool season grass (adapted from Phene et al. 1992)

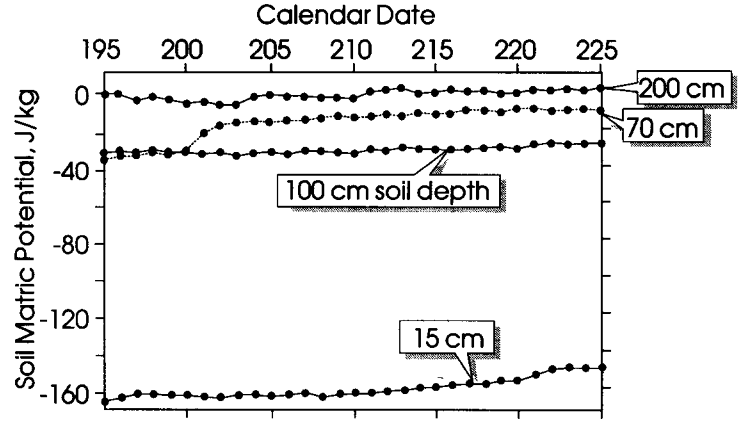

Fig. 7. Mean daily matric potentials through the soil profile with a water table at a depth of 2.0 m. Data are from the maturation phase for tomato in 1987 using a subsurface microirrigation system installed at a depth of 45 cm (adapted from Phene et al. 1989)

Subsurface microirrigation

The operational characteristics and advantages of subsurface microirrigation systems (SMS) relative to surface microirrigation as well as other irrigation methods have been described as: the surface soil layer is kept dry when the SMS is installed well below the soil surface thereby limiting evaporation to vapor diffusion through a dry soil; the wetted soil volume and a net upward hydraulic gradient can be maintained relatively constant when irrigations are applied frequently to replace soil water loss precisely; water and nutrients are applied near the center of the root system; and soil surface properties that frequently reduce infiltration and increase surface runoff are not a concern (Phene et al. 1987).

One of the advantages of SMS is minimization of soil evaporation. Evaporation from a bare clay loam soil irrigated by a microirrigation system placed at a depth of 45 cm was compared with both evaporation from the same type of system place on the soil surface (MS) and evaporation from several consecutive rainfall events (Fig. 6). Irrigation occurred several times daily for both the MS and SMS systems. The comparisons, performed in lysimeters, could not be done simultaneously. Thus, bare soil evaporation (E_{BS}) measured on one weighing lysimeter was reported as a ratio of evapotranspiration of a cool season grass (ET_0) from an adjacent weighing lysimeter to facilitate comparisons (Phene et al. 1992). The results illustrated in Fig. 6 indicate that the average ratio of E_{BS}/ET_0 was 0.06 for SMS. Thus only 6% of the total amount of ET_0 went to evaporation. This is less than half the amount when the microirrigation system was placed on the soil surface. Bare soil evaporation under similar circumstances, but triggered by rainfall, was ten times larger. In addition to minimizing evaporation from the soil surface, the dry surface soil restrains weed growth and permits implement traffic while irrigating (Phene et al. 1987).

During an experiment with SMS, Phene et al. (1989) monitored soil matric potential through the soil profile at hourly intervals. Applying a 1 mm depth of irrigation whenever 1 mm of water was lost from the lysimeter resulted in a nearly constant soil matric potential profile (Fig. 7) and an upward hydraulic gradient (Fig. 8). Figure 7 shows a relatively dry soil at a depth of 15 cm (matric potential of −160 J/kg) and a relatively wet subsoil (between 0 and −40 J/kg). Soil matric potential was nearly constant at all soil depths confirming a match between water supplied and water consumed. The largest deviation from a constant profile was a decrease in matric potential from −35 to −15 J/kg beginning on day 200.

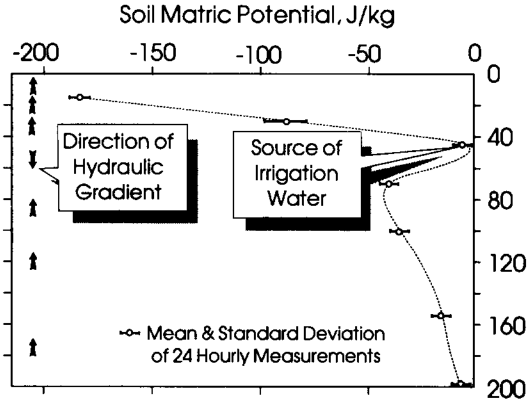

Fig. 8. Direction of the hydraulic and the matrix potential through a soil profile with a subsurface microirrigation system installed at a depth of 45 cm for a tomato crop on day 195 of 1987 with a water table depth of 200 cm (adapted from Phene et al. 1989)

The hydraulic gradient was shown to be upward on day 195 (Fig. 8) except between a soil depth of 45 and 70 cm where it was downward. The deviations of the matric potential values given in Fig. 8 indicates the variation in hourly readings throughout the day. These results indicate that when rainfall is negligible during the irrigation season, the hydraulic gradient can be maintained upward if desired with the precision of water management possible with SMS. Of course, a downward gradient in the lower reaches of the profile could be established by applying more water.

Table 3. Crop yield and water use efficiency of processing tomato grown wiht precise fertilizer applications through microirrigation systems in California (adapted from Phene et al. 1992)

System placement	1984 Nitrogen		1985 Nitrogen and Phosphorous		1987 Nitrogen + Phosphorous + Potassium	
	Commercial yield Mg/ha	Water-use* efficiency kg/m^3	Commercial yield Mg/ha	Water-use efficiency kg/m^3	Commercial yield Mg/ha	Water-use efficiency kg/m^3
On surface	126a**	19a	152b	20b	201b	29b
45-cm deep	121a	18a	168a	22a	220a	31a

* Water-use efficiency is defined as the ratio of fresh matter yield per unit of evapotranspiration

** Mean separation within columns by Duncan's Multiple Range Test at 5% level

Table 4. Water balance for several crops irrigated by subsurface microirrigation from 1984 to 1990 in the San Jaoquin Valley of California (adapted from Phene et al. 1992)

Year	Crop	Reference ET	Crop ET	Precipitation	Irrigation	Drainage
		mm	mm	mm	mm	mm
1984	Tomato	1823	959	104	692	–*
1985	Tomato	1720	855	127	792	59
1986	Cantaloupe	1701	863	167	552	90
1987	Tomato	1657	793	187	658	36
1988	Cotton	1583	979	205	694	83
1989	Sweet Corn	1514	693	86	667	2
1990	Tomato	1618	875	145	773	38
Mean		1659	860	146	690	51

* Experiment initiated with a dry soil profile, no drainage was measured

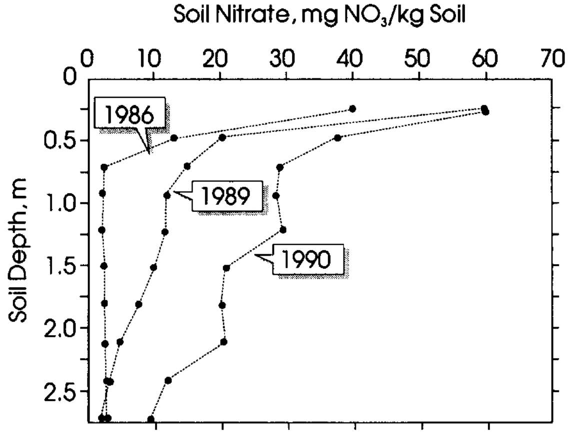

Fig. 9. Nitrate concentrations in a deep Panoche clay loam soil following three of the seven study years irrigated with a subsurface microirrigation system in the San Joaquin Valley of California. (Adapted from Phene, et al. 1992)

In addition to precise water management, SMS offers the opportunity for precise management of fertility. Phene et al. (1988) have demonstrated yield enhancement of processing tomatoes through daily nutrient applications in the irrigation water. Matching the plant uptake rates of nitrogen, phosphorus, and potassium by applications through the microirrigation system increased yields by more than 50% compared to meeting the N-demand alone (Table 3). This increased yield occurred without any relative change in evapotranspiration; the ratio of crop evapotranspiration to reference evapotranspiration actually dropped slightly over the three years of study.

Soil nitrate concentrations for three of the seven (1984–1990) seasons reported by Phene et al. (1988) are shown in Fig. 9. Nitrates accumulated in the upper soil profile above a depth of 50 cm and a relatively small amount of nitrate leached below the root zone. In view of the high yields and the large amount of nitrogen injected into the irrigation water (200 to 300 kg/ha each year except in 1990 when 540 kg/ha was applied), the amount of nitrate in the lower soil profile is relatively low. In 1986, following three cropping seasons, most of the nitrate was above 75 cm and nitrate concentrations below 75 cm were less than 5 mg of N/kg of soil. By 1989, the nitrate concentration had increased at all depths but was less than 5 mg/kg below a depth of 2 m. Following planned excessive nitrogen applications of nearly double the amount applied in earlier years, nitrate concentration in 1990 was higher than previous years by about double, and exceeded 10 mg/kg at a depth of 2.5 m.

The salinity hazard that may accompany such an efficient irrigation system is of paramount concern. The more precisely irrigation matches crop ET the higher the probability that salinity management will be required. If salinity is a concern, SMS must be managed carefully. When rainfall is insufficient to leach excessive salt concentrations, irrigation waters must be applied to the soil surface, particularly for seed germination.

During the seven year study of Phene et al. (1988), the components of the annual water balance and soil salinity were measured. The annual water balance components are summarized in Table 4. Values for reference ET and precipitation were obtained from a nearby weather sta-

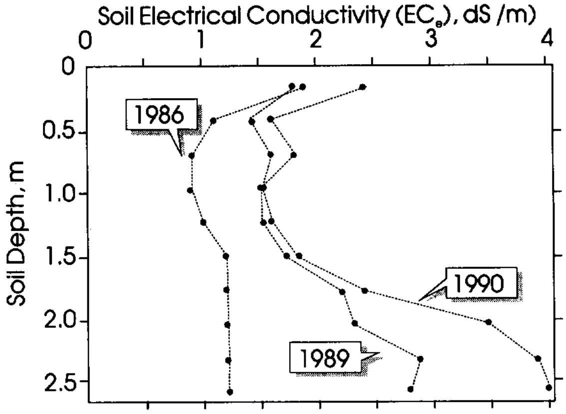

Fig. 10. Soil salinity, reported as the electrical conductivity of saturated extracts, for a deep Panoche clay loam soil during seven cropping seasons with a subsurface microirrigation system installed at a depth of 45 cm prior to the 1984 cropping season in the San Joaquin Valley of California (adapted from Phene et al. 1992)

tion. Crop ET, irrigation, and drainage were measured by a weighing lysimeter (Phene et al. 1989). Crop ET represents evapotranspiration for the entire year and averaged 52% of the annual reference ET. Soil water content for the 2.25-m-deep lysimeter, was reduced an average of 68 mm each year. The 51 mm of annual drainage amounts to a steady state leaching fraction of 0.06. Most of the drainage occurred in conjunction with sprinkler irrigation for seed germination and precipitation early in the cropping season.

Soil salinity at the end of three of the seven irrigation seasons is presented in Fig. 10. The electrical conductivity of the irrigation water averaged 0.4 dS/m. The highest levels of soil salinity occurred following the 1989 season when only 2 mm of drainage was measured. Assuming the root zone for the crops studied does not extend below 2 m, average soil salinity does not exceed the salt tolerance threshold for any of the crops studied (Maas and Hoffman 1977).

Irrigation management

Irrigation scheduling

Irrigation scheduling is determining the timing and quantity of water applications. To schedule irrigations accurately, the soil-plant-atmosphere continuum must be considered as a physically-integrated, dynamic system in which transport processes occur interactively (Philip 1969). Hence, a system that monitors throughout or integrates across the continuum is probably required to maximize water-use efficiency; unfortunately, such a monitoring system does not exist. In practice, irrigators select a part of the continuum to sense and then manage irrigations based upon empirical relationships between the variable monitored and crop productivity. Currently, irrigations are scheduled based on measurements of soil water, plant water status and/or the microclimate. Reasonable water-use efficiencies have been achieved by this practice largely due to the large buffer capacity of most soil-plant systems for water. As we strive for maximum efficiency, reliance on point measurements in the continuum and empirical relationships will be replaced by enhanced understanding of the physical and biological systems and the ability to take advantage of this improved understanding.

The amount or the energy level of water contained in the soil profile is often monitored to indicate the availability of water for crop consumption. Soil water impacts plant growth directly through its controlling effect on plant water potential and indirectly through its effect on aeration, temperature, and the transport, transformation, and uptake of nutrients. The traditional method of scheduling irrigations based upon soil measurements is to monitor the moisture reserve of the root zone as it diminishes following each irrigation to detect when the reserve has been depleted to some predetermined limit. When the limit is reached, an irrigation is applied to replenish the soil reservoir. A precondition to effective management is the knowledge of the crop rooting depth and the lower limit of soil moisture available to crops. Currently, soil water is typically managed to permit about 50% of the "available" water to be depleted before an irrigation. In addition to measuring water content, water potential expressed as the energy required to remove water from the soil is acknowledged as an important variable in the soil-plant-atmosphere continuum. Soil water content alone does not indicate how water moves within the soil profile or how much is available to the plant without undue stress. On the other hand, soil water potential does not give the amount of water present. Hence, both measures must be considered when relating irrigation to crop productivity. Information on the rate of soil water movement is also important to minimize unwanted deep percolation when scheduling irrigations. Unfortunately, flux measurements can not be made readily.

A plant responds to its total environment and is the interface between its source (soil) and sink (atmosphere) for water. A direct solution to scheduling irrigations is to interrogate the plant to assess its water status. In general, three types of methods have been developed to determine plant water status: destructive sampling, non-destructive contact monitoring, and remote sensing. All three types, in various forms, are available for commercial application. Destructive measurements consist of removing plant parts and measuring their water content or water potential. Plant water potential, a measure of the energy status of water in the plant, can be measured by thermocouple psychrometers or pressure chambers. Non-destructive, contact methods involve attaching devices directly to the plant to measure diameter or thickness, transpiration, photosynthesis, or stomatal conductance. Non-contact, non-destructive methods sense emitted or reflected radiation to assess plant health or the impact of cumulative stress. To date, however, no method is completely satisfactory or capable of achieving extremly high water-use efficiencies.

As the sink for evaporation and transpiration from the plant-soil system, the micro-environment can be measured to estimate the potential for water vapor to move into the atmosphere. Models using atmospheric variables to calculate potential evapotranspiration require numerous and frequent measures of temperature, humidity, radiation, wind, and precipitation. Direct measurements of evapotranspiration can be made with lysimeters or eddy correlation methods. Indirect measures include soil water balance, energy balance, Bowen ratio, chamber techniques, and stem flow methods.

As constraints on water availability and requirements for environmental protection increase, implementation of irrigation scheduling will be paramount. Sensors or methods such as those described above will serve as inputs to computers that will calculate water and nutrient status and activate the irrigation system to apply the appropriate amounts of water, nutrients, and pesticides on a timely basis. It is probable that in the future this ambitious monitoring and control task will be accomplished using remote sensing and/or transmission of the monitored data by satellite.

Irrigation control

A promising development beyond scheduling is controlling irrigation systems. Control systems require components for sensing, communicating and actuating the system based on decision algorithms. Current developments have utilized one or more of the required components, but to our knowledge no fully developed control system exists that can respond to an array of objectives without personal intervention.

Several examples of irrigation control systems are available. One of the first systems in the U.S. Great Plains was a system to monitor the electrical load demand of a farm to respond to the electrical supplier's need to maintain the electrical load of substations below critical levels (Heermann et al. 1984). This control system maintains an account of which center pivots are currently operating and which of the active systems are shut down in response to an electrical demand overload. Current commercial systems allow the irrigator to change the speed of rotation remotely and therefore the depth of application in each sector of the field. The systems also provide for monitoring operations and for changing the direction of rotation at a specified angle of rotation. Many systems can monitor and control several pivots and provide emergency shutdown warnings. To date, control systems for center pivots have not progressed beyond traditional irrigation scheduling procedures and do not directly employ sensing features, although some sensing is possible.

Some control systems for trickle irrigation systems are initiated by sensing soil water status. The lysimeter system of Phene et al. (1989) is an example of a controlled system that replaces evapotranspiration periodically. However, even this elaborate system does not include a decision algorithm that responds to varying economic, environmental or resource constraints.

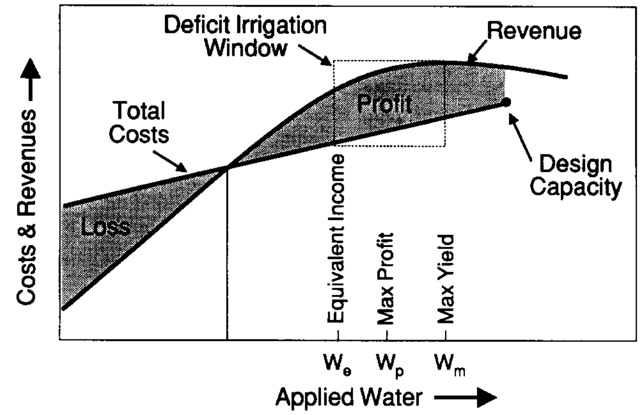

Fig. 11. Revenue and cost as functions of applied water (adapted from English et al., 1990)

A control system for furrow irrigation that reacts to the current infiltration rates and hydraulic conditions in the field has been developed (Latimer and Reddell 1990). With this method the rate of water advance on the first irrigation set of a field is monitored. Based on these data the infiltration rate is determined and used to determine irrigation applications on the remaining sets in the field. This system has the potential to improve furrow irrigation management but to date the system still requires an irrigator to make adjustments and cycle water to future sets.

An emerging area of irrigation control is prescription irrigation where the amount of water to apply to a parcel of land is determined based on the existing conditions on that parcel, future water supplies, and economic and environmental constraints and objectives. These types of systems will require development well beyond currently available technology and will increase the complexity of management. An information management system is needed to ensure that a record is maintained of past activities so that future decisions are based upon current conditions and knowledge of the historical conditions of the field. Regardless of the development and management problems associated with prescription irrigation, the potential economic and environmental benefits appear to be quite favorable and will spur the development of such "smart" systems.

Deficit irrigation

Deliberately managing crops to create a prescribed water deficit which results in a yield reduction is frequently called deficit irrigation (English et al. 1990). The goal, of course, is to increase water-use efficiency, either by reducing irrigation adequacy or by eliminating the least productive irrigations. When water costs are high or water supplies are limited, the appropriate amount of irrigation is less than that required for maximum yield. Likewise, when there are capital, energy, labor, or environmental constraints, deficit irrigation is a strategy to increase profits. The potential benefits of deficit irrigation arise from lower production costs and enhanced water-use efficiency. Techniques for irrigation involve limiting application depths, such that a portion of the field is underirrigated, and controlling irrigation frequency. As adequacy is reduced, application efficiency increases.

Management strategies for deficit irrigation are illustrated by comparing revenue and costs as functions of applied water in Fig. 11. The curvilinear line represents gross income, the product of yield and crop price. This revenue function has the same shape as a crop production function. The linear function in Fig. 11 represents total production costs and includes three important features. One feature is the intercept with the vertical axis, which is associated with the fixed costs of production. The variable costs are represented by the slope of the costs function. The third feature is the upper limit of the cost function and is the system's design capacity to deliver water. The cost function is not necessarily linear as represented in Fig. 11. Profit is the difference between the cost and revenue curves.

The amount of applied water that results in the maximum crop yield is denoted as W_m in Fig. 11. If additional water is applied, profit is reduced. Applying less water results in an increase in profit as variable costs decline faster than revenues. Maximum profit occurs when the cost of an additional increment equals the slope of the revenue curve (W_p in Fig. 11). As water applied is reduced further, a point (W_e) will be reached where the net income equals the net income at W_m. Between W_e and W_m, deficit irrigation is more profitable than full irrigation.

Deficit irrigation is widely practiced, particularly in water short areas. In India, planners have assumed that the water supply will be fully utilized about five out of ten years (Chitale 1987). Trimmer (1990) estimated that overall water supply delivered to farms in Pakistan is 35% below full crop water requirements if the entire cultivatable area is cropped. Deficit irrigation is also practiced in the U.S. Great Plains with the most extensive use of deficit irrigation in the Texas High Plains.

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