SUBSURFACE DRIP IRRIGATION: STATUS OF THE TECHNOLOGY IN 2010

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ABSTRACT. *Subsurface drip irrigation (SDI), although a much smaller fraction of the microirrigated land area than surface drip irrigation, is growing at a much faster rate and is the subject of considerable research and educational efforts in the U.S. This article discusses the growth of SDI, highlights some of the research and extension efforts, and points out some of the challenges to SDI adoption and some of the future opportunities for SDI.*

Keywords. *Irrigation design, Irrigation management, Microirrigation, Subsurface drip irrigation.*

Subsurface drip irrigation has been defined by ASABE as the application of water below the soil surface by microirrigation emitters with discharge rates usually less than 7.5 L h^{-1} (*ASAE Standards*, 2001). Subsurface drip irrigation (SDI) is different from, and should not be confused with, subirrigation, in which the root zone is irrigated by controlling the height of the water table.

The depth at which subsurface driplines are installed is selected according to crop, soil type, water source, pests, climate, tillage equipment, and producer preference. Some shallow SDI systems (<20 cm depth) are retrieved and/or replaced seasonally and have many characteristics similar to surface drip irrigation. Many research reports refer to these shallow systems as surface drip irrigation (DI) and reserve the term SDI for systems intended for multiple-year use that are installed below tillage depth (Camp and Lamm, 2003). The discussion here concentrates on SDI systems with driplines deeper than 5 cm that are intended for multiple-year use.

Although DI is now used more intensively than SDI, microirrigation probably started with water application below the soil surface (Davis, 1974). The first experiments with SDI began in the 1860s in Germany, where short clay pipes with open joints were used to provide both irrigation and drainage (Howell et al., 1983; Keller and Bliesner, 2000). In essence, SDI methodology evolved from the subirrigation method. The earliest SDI research in the U.S. that did not use subirrigation techniques was conducted at Colorado State University in 1913 by House (1918), who concluded that it was economically impractical. SDI has now been a part of modern agricultural irrigation since the early 1960s. Investigations of both SDI and DI with citrus crops and potatoes were conducted by Sterling Davis, an irrigation engineer with the U.S. Salinity Laboratory, in 1959 (Davis, 1974; Hall, 1985). At about the same time in Israel, Blass (1964) was reporting early experiences with SDI. SDI performance was often plagued by problems such as emitter clogging (chemical precipitation, biological and physical factors, and root intrusion) and poor distribution uniformity. However, as improved plastic materials, manufacturing processes, and emitter designs became available, a resurgence in SDI occurred in the 1980s, both in research activities and commercial operations (Camp et al., 2000).

GROWTH STATUS OF ON-FARM SYSTEMS

The use of SDI in the U.S. has increased from 163,000 to 260,000 ha in the five-year period 2003 to 2008, an increase of 59% according to the latest USDA Farm and Ranch Irrigation Survey (USDA-NASS, 2009). In comparison, the DI land area increased from 566,000 to 694,000 ha, a more modest increase of 23%. Nationally, SDI accounts for only about 27% of the land area devoted to the combined DI and SDI area (note: microsprinkler and bubbler irrigation are not included in these totals). However, this

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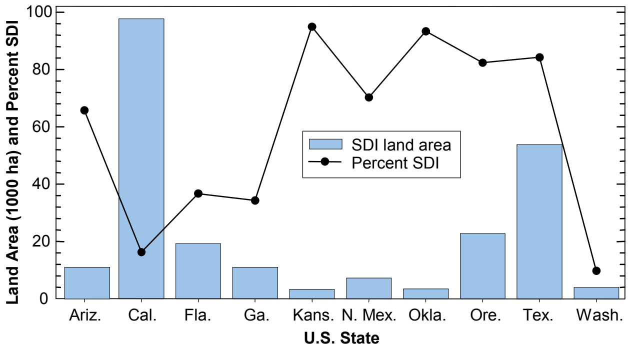

Figure 1. Characteristics of SDI usage in the ten U.S. states having the largest land area devoted to SDI. The percentage of SDI refers to the ratio of SDI to total drip-irrigated land area (total SDI and surface drip irrigation (DI)). Data summarized from USDA-NASS (2009).

comparison may be skewed by some SDI land area being reported as shallow, annually removed systems, which are not the focus of this article. The ten U.S. states with the largest SDI area comprise over 90% of the total SDI area but have a wide variation in the ratio of SDI/(SDI+DI) land area (fig. 1). This variation can probably be explained by the crop production in those states, with DI being used on higher-value crops (typically fruits, nuts, and vegetables) and SDI being used on lesser-value commodity crops (e.g., corn, cotton, and alfalfa). Subsurface drip irrigation can be perceived as harder to manage, mainly because it has fewer visual cues that irrigation problems are occurring. As a result, many producers growing the higher-value crops choose DI as a less risky option and because the cost of the irrigation system and its installation are not of paramount concern. When growing the lesser-value commodity crops with microirrigation, a deeper, multiple-year SDI system that can be amortized over several years is often the only economical option for a producer (Bosch et al., 1992; O'Brien et al., 1998).

Research and Educational Efforts

Considerable research is currently being conducted on SDI across the U.S. Three larger frameworks for some of this research exist within three separate regional research efforts: USDA-RRF Project W2128: Microirrigation for Sustainable Water Use (formerly W1128 and W128 from the western region of the U.S.), available at: www.cropinfo.net/W-128/w128.html; USDA-RRF Project S1018: Irrigation Management for Humid and Sub-Humid Areas (from the eastern region of the U.S.), available at http://nimss.umd.edu/homepages/home.cfm?trackID=4575; and the USDA-ARS Ogallala Aquifer Program: Sustaining Rural Economies through New Water Management Technologies, available at www.ogallala.ars.usda.gov/. These three on-going research efforts probably encapsulate the bulk of the current U.S. SDI research efforts and help ensure a great amount of interconnection between individual research projects, minimizing duplication of effort and building on previous research.

Major educational and technology transfer efforts concerning SDI have also been conducted during the ten years since the ASAE Fourth Decennial Irrigation Symposium (ASABE, 2000). An effort sponsored by the ASCE Environmental and Water Resources Institute (EWRI) worked toward providing educational materials for the use of SDI in the humid regions of the U.S. The concentration of this effort began with a meeting held in Florence, South Carolina, in February 2001, where topics were narrowed and discussed and writing teams were assembled. The ASCE-EWRI project resulted in the publication of a series of articles on SDI for humid regions concerning site selection, system design, and system management (Dukes et al., 2005; Grabow et al., 2005; Haman et al., 2005) that have been adapted to specific southeastern states. Another educational effort currently underway is being conducted under the auspices of the USDA-ARS Ogallala Aquifer Program involving Kansas State University, Texas A&M University, and the USDA Agricultural Research Service. A series of papers was presented at the 2009 ASABE Annual International Meeting in Reno, Nevada, and at the 2009 Irrigation Association technical conference, along with some targeted SDI field days in Kansas and Texas. The goal of this effort has been technology transfer of a large number of SDI research efforts being conducted by the project participants over the last 20 years and to indicate that SDI technology can be successfully adapted to U.S. Great Plains crops and conditions. These activities are summarized at: www.ksre.ksu.edu/sdi/SDITTstor/SDITTPublic.htm. Additionally, USDA-RRF Regional Projects W2128 and S1018 have outreach products as part of their goals.

Some of these research and educational efforts are expanded upon in later portions of this article that deal with individual topic areas.

Challenges to SDI Adoption and Successful Use

A list of SDI challenges was developed based on the authors' perceptions, experiences, and discussions with producers in their region of the U.S. Although this listing cannot be considered all-inclusive or scientifically authoritative, it may provide a general perspective of specific problems in different regions of the country as well as problems common to all regions. The challenges can be broadly categorized into design and installation (table 1), operation and management (table 2), cropping (table 3), and maintenance (table 4).

A few general comments can be drawn from table 1. First, it can be observed that when new technologies such as SDI first appear in a region, there is often a lack of expertise and providers for the technology. As growers themselves often know little about the SDI system, this can lead to communication problems, frustration on the part of system providers and growers, and often even an entry point for less-than-scrupulous providers. Fortunately, with consolidation and maturation in the SDI industry, it appears that industry is more responsive to these early markets and is working to "knock down" problems before they become widespread.

Second, installation depth continues to be a question, although in many cases it still seems to need a site and crop

Table 1. Design and installation challenges to SDI adoption and successful use in various irrigated regions of the U.S. (Note: Overlaps and interconnections may exist among tables 1 through 4).

Challenge	Southeast (humid and semi-humid)	Great Plains (generally semi-arid)	West (generally arid)
Designers, dealers, installers, after-sale support	A small number of qualified designers, dealers, and installers. Some systems are installed by growers, and there is some tendency to find less expensive options that may increase risk of system problems. Growers often do not understand sensitivity of the system to hydraulics.	Large improvement in the number of designers, dealers, and installers and their qualifications in last ten years, particularly in the southern Great Plains. After-sale support is important and could use further improvement.	Generally not a problem in California, but still smaller numbers of qualified companies in the Pacific Northwest.
Installation depth	Generally about 0.25 to 0.30 m dripline depth. Some concern about appropriate depth on variable soil types within fields. Overburden in non-bridging coarser, sandier soils may cause difficulties in "opening" driplines after installation (i.e., dripline pressure may be insufficient to overcome the weight of overburden).	Some movement away from deeper installation depths of 0.35 to 0.45 m toward shallower 0.25 to 0.3 m depths in hope of improving germination and early crop growth. Heavy soil textures may limit installation depth.	Some deeper (>0.2 m) systems for trees and vines, but greater use of install-and-remove systems for row crop fruits and vegetables. Power requirements for deeper installations in tree and vine crops.
		Deeper installations increase difficulty in finding and repairing dripline leaks. Concerns about root intrusion.	
Dripline spacing	Generally, alternate row middles (one dripline centered between adjacent pairs of crop rows), but grower questions arise on variable soil types and where crops of different row spacing are rotated.	Almost exclusively alternate row middles, except for some shallow-rooted vegetables, crops grown on coarse sandy soils, or where soil salinity is an issue.	Some issues about where to put driplines and how many driplines are required for tree crops. Lack of understanding how soil texture changes can affect design.
	GPS installation should be used for all row crop installations to increase tillage options and to reduce crop germination and growth problems.		

specific answer. If this remains the case, it may be useful for those entities providing technical advice to growers on the installation depth to be conceptually well grounded about what depth issues might arise and not to just rely on past experiences. A number of good reference sources exist for discussion of dripline depth conceptual issues as well as many other design issues (Hanson et al., 1997; Van der Gulik, 1999; Burt and Styles, 2007; Lamm and Camp, 2007; Lamm, 2009).

Finally, SDI dripline spacing is another question that must be answered early in the design process, and the reference sources mentioned in the previous sentence can help provide a good conceptual grounding. As a general rule, SDI dripline spacing is a multiple of the crop row spacing, whereas emitter spacing is usually related to the plant spacing along the row (Camp, 1998). Providing the crop with equal or nearly equal access to the applied water should be the goal of all SDI designs, but this presents a conflicting set of constraints when crops with different row spacing are grown with SDI. Mismatched crop row/bed and dripline spacing may not only result in inadequate irrigation and salinity problems but also in increased mechanical damage to the SDI system (Ayars et al., 1999). Adoption of similar row/bed spacing for crops on a farming enterprise may be advantageous, provided that the crops produce adequate yields under that spacing. The use of a real-time kinematic global positioning system (RTK-GPS) for SDI installation and cultural practices during the cropping season should be strongly considered. A GPS allows the distance between seed beds, SDI laterals, and tillage implements and other machinery to be controlled to within a few centimeters. Accurate lateral and crop placement can be critical in ad-

Table 2. Operation and management challenges to SDI adoption and successful use in various irrigated regions of the U.S. (Note: Overlaps and interconnections may exist among tables 1 through 4).

Challenge	Southeast (humid and semi-humid)	Great Plains (generally semi-arid)	West (generally arid)
Monitoring and evaluating performance	Fewer visual indicators of performance, and no wet soils qualitatively indicating amount of irrigation. Uncertainty about trusting performance to flowmeters, pressure gauges, and other sensors. Reluctance to learn new management styles and to accept new techniques of evaluating irrigation amount and performance. Growers have less overall understanding of performance that they cannot see.		
			Lack of trust in performance indicators leads to abandonment or lack of adoption of SDI in favor of DI, particularly for higher-value crops.
Irrigation scheduling and management.	Difficult for growers to learn and adopt new management strategies required for SDI, which are usually quite different from gravity or sprinkler irrigation. Minimizing drainage losses when irrigation scheduling is not used or is handled inappropriately. Water redistribution issues on coarse soils and fields with varying soils.		
			More studies and information are needed to manage regulated deficit irrigation (RDI) with SDI, although microirrigation will probably be a perquisite for RDI.

Table 3. Cropping challenges to SDI adoption and successful use in various irrigated regions of the U.S. (Note: Overlaps and interconnections may exist among tables 1 through 4).

Challenge	Southeast (humid and semi-humid)	Great Plains (generally semi-arid)	West (generally arid)
Crop germination and establishment	Can be a problem in all regions but is generally a larger problem in semi-arid and arid regions because of greater probability of having drier surface layers of soil.		
Build-up of salinity	Typically not a problem in humid regions.	Usually only a concern for a few crops grown under poor water quality, especially under deficit irrigation.	Can be a major problem. Crop rows and zones of soil salinity must be carefully managed.
Crop rotations	Peanuts, typically one of the irrigated rotational crops with the greatest net returns, are not well-suited for permanent SDI (harvesting issues).	Generally not a problem with grain and fiber row crop production. In the far-south Great Plains, there can be issues in vegetable producing areas, and sometimes shallow install/remove SDI or DI systems are used.	Multiple crop types with different row spacings, cultural practices, and irrigation management may favor install/remove DI over permanent SDI. Growers may lease fields or only return with a higher-value crop after a few years.
Crop development and growth	Peanuts may not peg properly into dry soil. Tomato yields were lower with SDI than with DI when grown on soils with excessive deep percolation in Florida.	Unexplained evidence from Kansas that kernel set in field corn may be decreased with SDI compared with LEPA (low energy precision application) sprinklers in extreme drought years.	
	Harvesting of some crops (e.g., peanuts, potato, sweet potato, and onion) where soil disturbance is required.		

dressing germination challenges, controlling the wetting front relative to the crop root zone (important for saline conditions, chemigation, and fertigation), and minimizing mechanical damage by tillage and other machinery, among other factors.

The dominant, regional cross-cutting operational challenge, as expressed in table 2, is removing the perception that SDI may be too hard to operate and manage when there is no "squirt to the dirt." This is particularly the case in regions where high-value horticultural, tree, and vine crops are grown, where the grower may have an erroneous perception that SDI presents more economic risk than DI because of the lack of easily observed indicators of SDI system operation and performance. The perception is real and was recognized early by Phene (1996) as a major impediment and has occurred in all regions. Producers managing large irrigated areas usually have very limited time available for various management aspects of their operations; therefore, they must rely heavily on visual clues concerning plant and soil water status. Other segments of the irrigation industry have even used this perception against SDI in the promotion of their own products. It remains a challenge and future need to develop reliable, easy to understand, and trustworthy tools and instruments to remove this impediment. Flowmeters and pressure gauges at appropriate locations within the SDI system can be effective tools, but growers still need to use this information consistently and properly. Time series of these two measurements can be used to monitor system performance and alert the grower to system concerns before the problems become unmanageable (fig. 2). Even in cases where a systematic irrigation management strategy has been implemented, such as the reference evapotranspiration - crop coefficient approach, overirrigation may still occur and result in deep percolation, poor soil aeration, and reduced crop yields (Colaizzi et al., 2004). It is quite conceivable that advances in soil water and plant water stress sensors coupled with irrigation flowmeter measurements might lead to a level of redundancy in SDI system performance information that would be considered acceptable to those subscribing to the "no visibility" perception. Such redundancy may also serve to reduce the management time required, which is an essential prerequisite for the adoption of any new technology.

Crop establishment is also a major impediment to the

Table 4. Maintenance challenges to SDI adoption and successful use in various irrigated regions of the U.S. (Note: Overlaps and interconnections may exist among tables 1 through 4).

Challenge	Southeast (humid and semi-humid)	Great Plains (generally semi-arid)	West (generally arid)
Filtration/ water treatment	All regions need good and reliable filtration systems and water treatment strategies that are cost-effective for the crops being grown. Growers often put off maintenance until problems are severe. Unproven water treatment technologies are being aggressively marketed, often delaying use of proven technologies. Growers may be frustrated with greater expenses.		
Clogging	Biological clogging concerns when surface water is being utilized.	Manganese clogging problems occurring in some regions of Texas.	Biological clogging concerns when surface water is being utilized.
	Iron bacteria and other associated iron problems arise in some locales. Often water chemistry and biological problems are site or region specific. In newer microirrigation regions, a dearth of expertise for the specific problem often exists, and the extent of the microirrigated area may not be able to attract the expertise that is needed.		
Root intrusion and root pinching		Alfalfa and other grasses are probably the only major concern, unless deficit irrigation is routinely practiced.	Potato, asparagus, and celery and some permanent crops can present root intrusion problems. Root pinching can occur in trees and vine crops.
Rodents	One of the most difficult maintenance issues to address when it occurs. All regions are susceptible.		
Longevity	Mixture of rotational crops may require considerable system longevity to justify adoption of SDI.	System longevity is crucial when considering lower-valued commodity crops such as cotton and corn.	Usually of less concern for higher-value crops such as fruits and vegetables.

Anomaly A: The irrigator observes an abrupt flowrate increase with a small pressure reduction at the zone inlet and a large pressure reduction at the flushline outlet. The irrigator checks and finds rodent damage. The irrigator repairs the dripline.

Anomaly B: The irrigator observes an abrupt flowrate reduction with small pressure increases at both the zone inlet and the flushline outlet. The irrigator checks and finds an abrupt bacterial flare-up in the driplines. The irrigator immediately chlorinates and acidifies the system to remediate the problem.

Anomaly C: The irrigator observes an abrupt flowrate decrease from the last irrigation event with large pressure reductions at both the zone inlet and flushline outlet. A quick inspection reveals a large filtration system pressure drop, indicating the need for cleaning. Normal flowrate and pressures resume after cleaning the filter.

Anomaly D: The irrigator observes a gradual flowrate decrease during the last four irrigation events with pressure increases at both the zone inlet and flushline outlet. The irrigator checks and find that the driplines are slowly clogging. The irrigator immediately chemically treats the system to remediate the problem.

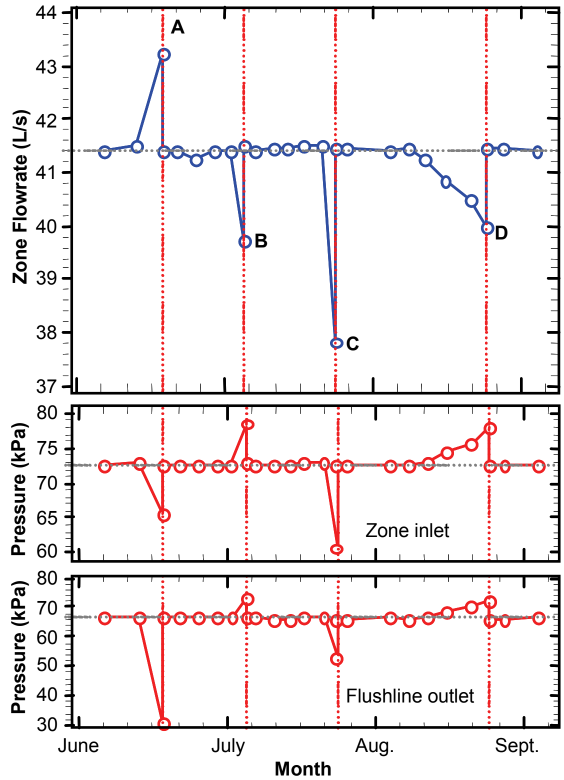

Figure 2. Hypothetical examples of how pressure and flowrate measurement records could be used to discover and remediate operational problems (after Lamm and Camp, 2007).

adoption of SDI (table 3). In some regions of the U.S., sprinkler systems are used to ensure crop establishment for high-value crops such as fruits and vegetables. In the Great Plains, multiple irrigation systems for the same parcel of land have not been considered economically feasible for the typical lower-value crops such as cotton and field corn. Generally, precipitation is adequate in the region for crop establishment of summer crops; however, crop establishment can still be a problem in dry years. In the Great Plains region, research efforts are currently underway by some of the authors to develop tillage and bed management strategies that can help reduce crop establishment problems. Tillage and planting practices can sometimes be used to prevent or avoid dry soil conditions that would impede crop germination and establishment. When applied irrigation does not move into the loosely consolidated soil surface layers in a bed cropping system, the dry soil near the surface can be removed to the traffic furrow, thus exposing wetter and firmer soils for crop establishment. Crop establishment with SDI can also be a problem on coarse-textured soils or when short drought periods occur at planting in the semi-humid and humid regions.

Saline water application through SDI may result in adverse salt build-up at the edge of the wetted soil volume or above the dripline in the seed or transplant zone, which can hamper crop establishment and plant growth (Hanson et al., 1997; Schwankl et al., 1998). Care must be taken in plant placement relative to the dripline position to avoid these high-salinity zones. Leaching of the salinity zone above the dripline is often necessary by sprinkler irrigation, but in some areas leaching is handled by dormant-season precipitation. In some regions, these difficulties in salinity management have reduced or prevented the adoption of SDI (Burt et al., 2003).

Rotation of higher-value crops with lower-value crops may present an economical barrier to adoption of SDI systems, especially when land areas are leased or when the rotation cycle between the higher and lower value crops is several years.

Certain crops may not develop properly under SDI in some soils and climates. For example, peanuts may not peg properly into dry soil, and some tree crops may benefit from a larger wetting pattern than SDI can provide in a typical system design. Greater corn grain yields were reported for SDI in three normal to wetter years in Kansas, but LEPA (low energy precision application) sprinklers obtained greater yields in four extreme drought years (Lamm, 2004). The differential yield response was attributed to differences in the corn yield components. Greater LEPA corn yields (approximately 0.9 Mg ha^{-1}) were associated with more kernels per ear as compared to SDI (534 vs. 493 kernels per ear) in the extreme drought years. Greater SDI yields (approximately 0.9 Mg ha^{-1}) were associated with greater kernel mass at harvest as compared to LEPA (347 vs. 332 mg per kernel) in normal to wetter years. The reason for these differences has not been determined, but new studies are underway. Tomato yields were decreased by 30% when using SDI, compared with DI, on a sandy soil in Florida (Clark et al., 1993) where deep percolation was excessive for this shallow-rooted crop.

Root crops such as sugarbeet, potato, and onion can present unique crop harvest challenges for SDI and, as a result, may not be good candidates for continuous, multiple-year SDI systems, although efforts have been made to overcome these obstacles (Abrol and Dixit, 1972; DeTar et al., 1996; Shock et al., 1998).

As with all microirrigation systems, water filtration is critical in ensuring proper system operation and system longevity (table 4). However, this issue becomes even more important for long-term SDI systems where duration of more than ten years is desired. SDI systems may require more complex water quality management than DI systems because there are no opportunities to clean the emitters manually. The added cost of complex water filtration and chemical treatment of marginal-quality water might further reduce the feasibility of SDI use on lower-value crops.

Maintenance is often perceived to be a less glamorous task by growers and may be neglected until SDI system problems are severe. Additionally, growers may not monitor their flowmeters and pressure gauges regularly enough to notice when problems are beginning to occur. In larger microirrigated regions (e.g., Florida and California), there has been an increase in the number of quality service companies that can help assess and remediate maintenance concerns. However, and particularly so in the smaller microirrigation regions where the SDI industry has not matured, buyers still need to beware of unproven technologies that may exacerbate the maintenance problems and add unnecessary costs.

Historically, as microirrigation is adopted in new regions of the U.S., water quality problems arise. Eventually, as the microirrigated area increases, there is enough impetus and interest to bring expertise to bear on the water quality problems. However, in the interim, early adopters of the technology experience greater difficulties, and when they have a system failure, it may set back adoption in the region. Hopefully, this challenge can be eliminated or reduced in the future by a combination of the resources of industry and the education sector to address these issues early in the SDI adoption phase.

Root intrusion or root pinching from some crops may limit SDI suitability. Some crops such as sweet potato, celery, asparagus, and permanent crops that have long periods when irrigation is minimal or terminated may exhibit high root intrusion into SDI emitters (Burt and Styles, 1999). In some areas, the herbicide trifluralin has been used either as an application through the tube or by impregnation into the microirrigation components (i.e., dripline or filter elements) for slow release to reduce root intrusion (Ruskin and Ferguson, 1998). Root pinching of the dripline can also occur with some tree and vine crops.

Rodents are one of the most difficult maintenance challenges with SDI because of the difficulty in locating the leak and also the difficulty of making repairs below ground. The difficulty in determining the actual location of a dripline leak caused by rodents is compounded by the fact that the leaking water may follow the burrow path for a considerable distance before surfacing. Anecdotal reports from the U.S. Great Plains can be used to describe some of the typical habitat scenarios that tend to increase rodent problems. These scenarios include close proximity of permanent pastures and alfalfa fields, railroad and highway easements, irrigation canals, sandy soils, and crop and grain residues during an extended winter dormant period, or absence of tillage. Cultural practices such as tillage and crop residue removal from around SDI control heads and aboveground system apparatus seem to decrease the occurrence of rodent problems. Some growers have tried deep subsoiling and/or applying poison bait around the SDI system field perimeters as a means of reducing rodent subsurface entry into the field. Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Deeper SDI depths (45 cm or more) may avoid some rodent damage (Van der Gulik, 1999). Many of the burrowing mammals of concern in the U.S. have a typical depth range of activity that is less than 45 cm (Cline et al., 1982). Some researchers have expressed the thought that rodent damage could be minimized by use of hard hose dripline rather than thin-walled tubing (Ayars et al., 1999).

The longevity of SDI systems is of great importance when lower-value commodity crops such as cotton and field corn are grown without rotation with higher-value crops. SDI systems need to have life spans of ten or more years on the larger irrigated fields ($\geq$60 ha) of the Great Plains when producing field corn to approach economic competitiveness with center-pivot sprinkler irrigation systems (O'Brien et al., 1998). Commercial systems in south Texas have been operated for over 20 years (Enciso-Medina et al., 2009), and a research system at Kansas State University has been operated for more than 20 years with little degradation in plot flowrates (Lamm, et al., 2009). The need for longevity when growing lower-value crops reemphasizes that system designs need to be adequate and that the maintenance regimen needs to be rigorous and consistent (Rogers and Lamm, 2009).

Opportunities Provided by SDI Adoption

Although the challenges to SDI adoption and successful use provided in this article and elsewhere (Lamm, 2009) can appear quite daunting, there can also be unique advantages to the use of SDI (Lamm and Camp, 2007). A few of these opportunities are discussed here with the goal of suggesting where future SDI growth may occur and also to outline future research needs. The partial listing below may stimulate thought about where other similar opportunities might occur.

Opportunity to Reduce Water Use and Improve Environmental Water Quality

Properly installed and managed SDI can be the most efficient method of irrigation, resulting in lower overall water and energy use to produce the globe's food needs. SDI also removes many of the water quality or pollution problems associated with alternative irrigation systems, such as off-field movement of sediment, fertilizers, and pesticides. These factors make SDI a very attractive irrigation alternative for preserving our natural resources and water quality.

Opportunity for Greater Use of SDI with Biological Effluents

The availability of freshwater sources for irrigation is diminishing in all parts of the world, and the conflicts between urban and agricultural interests for this water are continuing to increase. Microirrigation will continue to play a large role in the use of degraded water resources. The use of SDI for biological effluents in particular appears very promising in that it can limit human exposure to the waters and direct contact with fresh produce (i.e., fruits and vegetables that may be eaten uncooked) and thus possibly reduce water treatment needs and can also reduce odors. These are just a few of the potential advantages of using SDI with biological effluents, with a more complete listing provided by Trooien and Hills (2007).

Opportunity for Greater SDI Adoption on Small or Irregularly Shaped Fields

As older gravity/surface irrigation systems are being retired due to less irrigation efficiency or greater labor requirements, pressurized irrigation systems are being chosen. On small and/or irregularly shaped tracts of land, mechanical-move sprinkler irrigation systems can be more expensive than microirrigation systems. As early as 1982, SDI was suggested as a good, economical, irrigation alternative for small farmers in the U.S. (Mitchell and Tilmon, 1982). Subsurface drip irrigation systems may be the most likely replacement system on smaller farms and farm tracts because the system and installation costs can be amortized over many years, the system cost/land area ratio is relatively stable, and there is no large annual labor requirement for installation and removal.

Opportunity to Stabilize Crop Yields under Deficit Irrigation with SDI

Growing evidence from the southern Great Plains suggests that SDI can stabilize crop yields at a greater level than sprinkler irrigation when deficit irrigation is practiced (Bordovsky and Porter, 2003; Colaizzi et al., 2010). Since institutional and hydrological constraints may necessitate deficit irrigation in some situations and since the primary focus of irrigation is to obtain greater economic returns, SDI may allow a greater level of economic returns that are necessary to support rural communities in the Great Plains.

Opportunity for Improved and More Flexible Cropping with SDI

Alfalfa, a forage crop, has high crop water needs and thus can benefit from highly efficient irrigation systems such as SDI. In some regions, the water allocation is limited by physical or institutional constraints, so SDI can effectively increase alfalfa production by increasing the crop transpiration while reducing or eliminating soil evaporation. A major advantage of SDI on alfalfa is the ability to continue irrigating immediately before, during, and immediately after the multiple seasonal harvests. Continuation of irrigation reduces the amount of water stress on the alfalfa and thus can increase forage production, which is generally linearly related to transpiration. Transpiration on SDI plots that did not require cessation of irrigation was 36% higher during this period than on plots where irrigation was stopped for the normal harvest interval (Hutmacher et al., 1992). Yields with SDI were approximately 22% higher than surface flood-irrigated fields while still reducing irrigation requirements by approximately 6%. Water use efficiency was increased mainly due to increased yield, not less water use (Ayars et al., 1999).

On some nut tree crops, especially almonds and walnuts, harvest is accomplished in phases (trees are shaken so nuts can fall to the ground, nuts are allowed to dry on the ground, and then nuts are picked up). Growers often need to irrigate during the extended harvest period while the nuts are being allowed to dry on the soil surface. Irrigating at this time with alternative irrigation systems without rewetting and damaging the nuts is difficult, but it can be accomplished with SDI. Irrigation during this period helps keep the trees healthy and prevents premature senescence, which is particularly important when there are multiple varieties in the grove having different maturity dates (L. J. Schwankl, University of California-Davis, personal communication, 2002). SDI systems also are less susceptible to mechanical damage during the multiple harvest operations, and the drier soil surfaces provided by SDI reduce weed pressure that would interfere with raking and vacuuming of the nuts at harvest.

In orchards and vineyards, the greatest perceived advantages of SDI are that it allows uninterrupted crop cultural practices, such as multiple harvests, spraying, thinning, pruning, mowing, and tilling without interference from the irrigation system or wet soils. Subsurface drip irrigation also reduces weed germination and growth in the wide spaces between rows and therefore significantly reduces mowing, spraying, and other weed control or cover-crop maintenance costs (Edstrom and Schwankl, 1998).

One major cotton producing area in the U.S. Southern Great Plains is centered at Lubbock, Texas. It appears that SDI has been adopted on more land area here for cotton production than anywhere else in the U.S., largely because SDI is particularly amenable to production systems based on deficit irrigation (Bordovsky and Porter, 2003; Colaizzi et al., 2010; Enciso-Medina et al., 2007). In recent years, cotton production has expanded northward to the northern Texas Panhandle and into parts of southern Kansas, where irrigated corn has typically been produced. Both crops have similar revenue potential, but cotton has about half the irrigation requirement of corn, which is an important consideration in the semi-arid regions that are dependent on the Ogallala Aquifer for irrigation. The Ogallala Aquifer has declined throughout Texas, Oklahoma, and Kansas because withdrawals (mostly for irrigation) have greatly exceeded recharge. Anecdotal evidence suggests that cotton matures earlier under SDI compared with center-pivot irrigation, which is thought to be related to the reduced evaporative cooling of plants and soils that results with SDI. On a clay loam soil at Bushland, Texas, SDI maintained warmer soil temperatures and resulted in consistently greater cotton lint yield across a variety of irrigation treatments compared with LEPA or spray irrigation (Colaizzi et al., 2010). These results suggest that SDI has advantages over center-pivot irrigation for cotton production in thermally limited climates.

CONCLUSIONS

Increases in SDI research, education, and commercial activities are continuing to occur in the U.S. The improvements in SDI components and associated microirrigation products that occurred prior to the 4th Decennial National Irrigation Symposium, which were highlighted by Camp et al. (2000), have allowed for greater commercial adoption of the systems. These systems can have a long commercial life (>20 years). Substantial challenges exist, thwarting wider adoption of SDI systems. Some of these challenges are basically decision points where growers may decide that an alternative irrigation system is legitimately in their best interest. Other challenges are caused by lack of appropriate information or uncertainty concerning the operation and management of the SDI system. The perception that SDI systems are difficult to manage and that the lack of visual cues about SDI system performance should preclude its adoption are widespread and are not easy to remove. Better management tools and guides and redundancy in providing real-time system performance parameters might help reduce this perception. Research and educational efforts by industry, USDA, state and local water agencies, and universities are still needed to further advance this relatively new technology, which is generally <50 years old in modern usage. Filtration and water treatment to avoid emitter clogging, the preeminent maintenance requirement for all microirrigation systems, could benefit from even closer management with SDI, since these systems are intended for multiple years of use without replacement and because the systems are below the soil surface. Although many growers have been able to cope with rodent damage to their SDI systems, rodent management remains as a large barrier to widespread adoption of SDI. Strong efforts should be made to develop solutions to this problem.

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