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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 United States. This paper will discuss the growth in SDI, highlight some of the research and extension efforts, and point out some of the challenges to SDI adoption and some of the future opportunities for SDI.*

Keywords. Microirrigation, subsurface drip irrigation, irrigation design, irrigation management.

Introduction

Subsurface drip irrigation has been defined by ASABE to be the application of water below the soil surface by microirrigation emitters with discharge rate usually less than 7.5 L/h (ASAE S526.2, 2001). Subsurface drip irrigation (SDI) is different from, and should not be confused with, subirrigation where 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, 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). Discussion here will concentrate 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 United States 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 United States 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, resurgence in SDI occurred, both in research activities and commercial operations (Camp et al., 2000).

Growth Status of On-Farm Systems

The use of SDI in the United States 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 not included in these totals). However, this comparison can perhaps be skewed by the fact that some of the SDI land area being reported is shallow, annually removed systems which are not the focus of this paper. The ten US 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 (Figure 1). The variation can probably be explained by the crop production in those states with DI being used on greater-value crops (typically fruits, nuts, and vegetables) and SDI being used on lesser-value commodity crops (e.g., corn, cotton and alfalfa). There can be the persistent perception that SDI is harder to manage mainly because it has less visual cues that irrigation problems are occurring. As a result, many producers growing the greater-value crops choose DI as a less risky option and because 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.

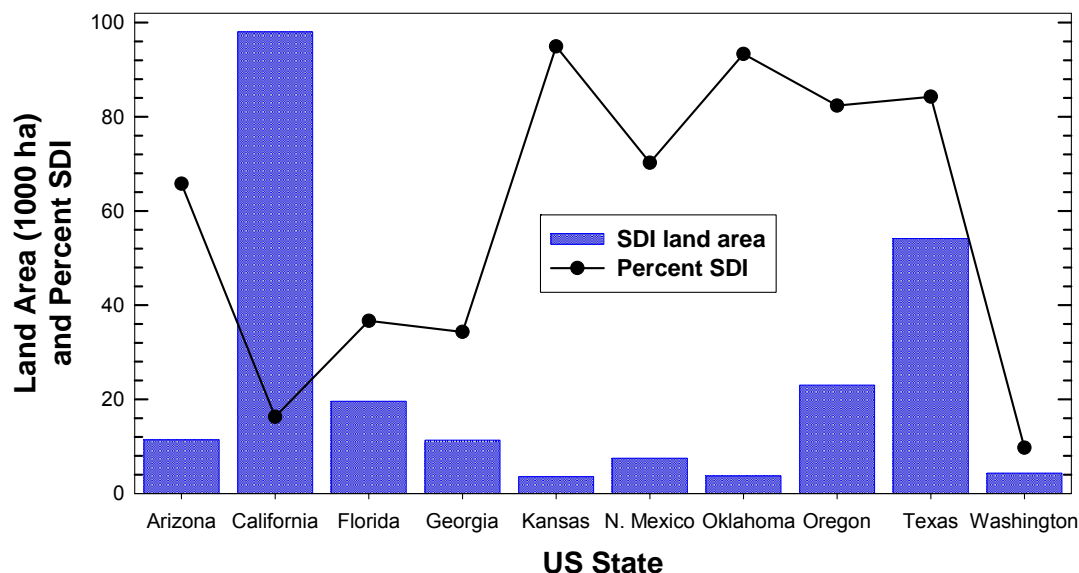


Figure 1. Characteristics of SDI usage in the ten U.S. states having the largest land area devoted to SDI. The percentage of SDI refers to the ratio of SDI to total SDI and surface drip irrigation (DI). Data summarized from USDA-NASS (2009).

Research and Educational Efforts

Considerable research is being conducted on SDI across the United States at the current time. 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 previously W128), website at <http://www.cropinfo.net/W-128/w128.html>, USDA-RRF Project S1018, Irrigation Management for Humid and Sub-Humid Areas, website 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, website at <http://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 assure a great amount of interconnection between individual research projects, minimizing duplication of effort and building upon 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. An effort sponsored by ASCE-EWRI worked towards providing educational materials for the use of SDI in the humid regions of the United States. 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. This 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 were presented at the 2009 annual meeting of the ASABE 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 twenty years and to indicate that the SDI technology can be successfully adapted to US Great Plains crops and conditions. These activities are summarized at <http://www.ksre.ksu.edu/sdi/SDITTstor/SDITTPublic.htm>. Additionally, the USDA-RRF regional projects W2128 and S1018 have outreach products as part of their goals.

Some discussion of parts of these research and educational efforts will be expanded upon in later portions of this paper dealing 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 United States. 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).

Table 1. Design and installation challenges to SDI adoption and successful use in various irrigated regions of the United States. Note: There can be overlap and interconnections 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	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 don't understand sensitivity of system to hydraulics.	Large improvement in number of designers, dealers and installers and their qualifications in last ten years, particularly in 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 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	Some movement away from deeper installation depths of 0.35 to 0.45 m towards 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 & 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.	

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, though in many cases it still seems to need a site and crop specific answer. This may always be the case, so 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. There are a number of good reference sources for discussion of the dripline depth conceptual 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. Providing the crop with equal or nearly equal opportunity to the applied water should be the goal of all SDI designs. 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. There is a need to strongly consider use of GPS systems for SDI installation and during the cropping season. A GPS, system allows the distance between seed beds, SDI laterals, and tillage implements and other machinery to be controlled to within a few cm. This may be critical in addressing 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 predominant, 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’s 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. This 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 (Figure 2). Even in cases where a systematic irrigation management strategy has been implemented, such as the reference evapotranspiration – crop coefficient approach, over-irrigation may still occur and result in deep percolation, poor soil aeration, and reduced crop yields (Colaizzi et al., 2004). It

is easily 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 management time required, which is an essential prerequisite for the adoption of any new technology.

Table 2. Operation and management challenges to SDI adoption and successful use in various irrigated regions of the United States. Note: There can be overlap and interconnections 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 they can't see.		Lack of trust in performance indicators leads to abandonment or lack of adoption of SDI in favor of DI.
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 prerequisite for RDI.

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 and 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. He 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. He immediately chemically treats the system to remediate the problem.

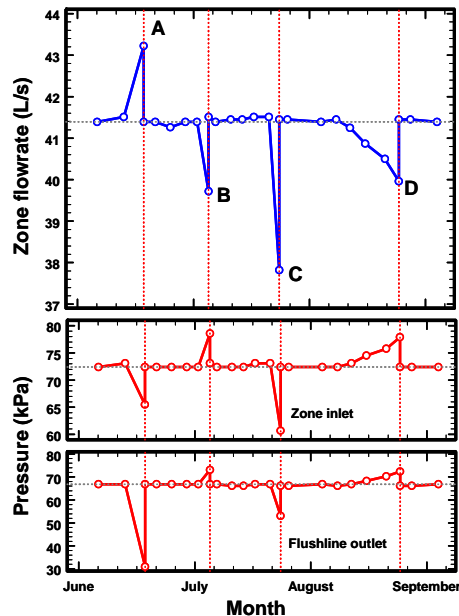


Figure 2. Hypothetical example of how pressure and flowrate measurement records could be used to discover and remediate operational problems (after Lamm and Camp, 2007).

Crop establishment is also a major impediment to the adoption of SDI. In some regions of the US, sprinkler systems are used to assure crop establishment for high value crops such as fruits and vegetables. This is not an economically feasible option for lower value crops such as cotton and field corn grown in the Great Plains. In this 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.

Table 3. Cropping challenges to SDI adoption and successful use in various irrigated regions of the United States. Note: There can be overlap and interconnections 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.		
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 greatest net returns, is not well-suited for permanent SDI (harvesting issues)	Generally not a problem with grain and fiber row crop production. In 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 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 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 sprinklers in extreme drought years.	
	Harvesting of some root crops (e.g., potato and onion) are difficult with SDI		

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. In some regions, these difficulties in salinity management have reduced or prevented the adoption of SDI (Burt et al., 2003).

Rotation of greater 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 greater 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) were associated with greater kernels/ear as compared to SDI (534 vs. 493 kernels/ear) in the extreme drought years. Greater SDI yields (approximately 0.9 Mg/ha) were associated with greater kernel mass at harvest as compared to LEPA (347 vs. 332 mg/kernel) in normal to wetter years. The reason for these differences has not been determined, but new studies are underway. Tomato yields were decreased 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 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. However, this issue becomes even more important for long-term SDI systems where duration of greater than 10 years is desired. SDI may require more complex water quality management than DI systems because there are no opportunities to clean 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 be monitoring their flowmeters and pressure gauges regularly enough and noticing that problems are beginning to occur. In the 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 being adopted in new regions of the United States, water quality problems arise and eventually as the microirrigated area increases there is enough impetus and interest to bring expertise to bear on the 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 for SDI by a combination of the resources of industry and the education sector to address these issues early in the 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). Root pinching of the dripline can also occur for some tree and vine crops.

Table 4. Maintenance challenges to SDI adoption and successful use in various irrigated regions of the United States. Note: There can be overlap and interconnections 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 that are being grown. Growers often put off maintenance until problems are severe. Unproven water treatment technologies are being aggressively marketed. This may delay use of proven technologies and frustrate growers 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. There is often a dearth of expertise for the specific problem and the scale of the problem in newer microirrigation regions 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 greater value crops such as fruits and vegetables.

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 the close proximity of permanent pastures and alfalfa fields, railroad and highway easements, irrigation canals, sandy soils, 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 above-ground 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 greater) may avoid some rodent damage (Van der Gulik, 1999). Many of the burrowing mammals of concern in the United States have a typical depth range of activity that is less than 45 cm (Cline et. al., 1982).

Longevity of SDI systems is of great importance when lower-value commodity crops such as cotton and field corn are being grown without rotation with higher-value crops. SDI systems need to have life spans of 10 or more years on the larger irrigated fields (≥ 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 twenty-plus 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 paper and elsewhere (Lamm, 2009) can appear quite daunting, there can be unique advantages to the use of SDI (Lamm and Camp, 2007). A few of these opportunities will be discussed here with the goal of suggesting where future SDI growth may occur and also to outline future research needs. The listing below should be considered just a partial listing but it 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. This can result in overall lower 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. This makes 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 is playing and 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 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 smaller and/or irregularly shaped fields

As older gravity/surface irrigation systems are being retired due to less irrigation efficiency or 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 system alternative for the small farmer in the United States (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 not a large annual labor requirement for installation and removal.

Opportunity to stabilize crop yields under deficit irrigation with SDI

There is growing evidence from the southern Great Plains 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 profitable economic activity to remain in 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 prior, 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 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 can be accomplished with SDI. Irrigation during this period helps keep the trees healthy and prevents premature senescence. This is particularly important if there are multiple varieties in the grove having different maturity dates (Schwankl, 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.

The US Southern Great Plains is a major cotton producing area and has traditionally been produced in an area centered at Lubbock, Texas. It appears that SDI has been adopted on more land area here for cotton production than anywhere else in the US, as SDI is particularly amenable to cotton production under 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 as corn, which is an important consideration in the semi-arid regions dependent on the Ogallala Aquifer for irrigation. The Ogallala has declined throughout Texas, Oklahoma, and Kansas because withdrawals (mostly for irrigation) have greatly exceeded recharge. There is anecdotal evidence that cotton matures earlier under SDI compared with center pivot irrigation, which is thought to be related to reduced evaporative cooling of plants and soils resulting 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). This would make SDI particularly advantageous over center pivot irrigation for cotton production in thermally-limited climates.

Conclusion

Increases in SDI research, education and commercial activities are continuing to occur in the United States. 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 a grower may decide that an alternative irrigation system is legitimately in their best interest. Other challenges are caused by lack of appropriate information or the uncertainty about information 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 the universities are still needed to further advance this relatively new technology (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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