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Managing the Challenges of Subsurface Drip Irrigation

Freddie R. Lamm, Professor and Research Irrigation Engineer

Kansas State University, Colby, Kansas, flamm@ksu.edu

Abstract. *This paper will discuss from a conceptual standpoint many of the challenges of subsurface drip irrigation (SDI). Topics will include soil water redistribution as affected by soil type and soil characteristics, nutrient availability, differential crop response, system installation concerns, and system maintenance issues. The paper and presentation will summarize material obtained by the author in preparing for a recent book chapter concerning SDI and will also show examples of the challenges as a tool to broaden their conceptual understanding. .*

Keywords. Emitter, microirrigation, irrigation design, SDI.

Introduction

Subsurface drip irrigation (SDI) is defined as the application of water below the soil surface by microirrigation emitters. The discharge rate of the emitters is usually less than 2 gal/h (ASAE S526.2, 2001). Some shallow subsurface systems (< 8 in depth) are retrieved and/or replaced annually and are very similar to surface drip irrigation. Many research reports refer to these systems as surface drip irrigation, and reserve the term SDI for systems intended for multiple-year use that are installed below tillage depth (Camp and Lamm, 2003). However, that is an arbitrary distinction based on usage rather than whether the system is installed below ground and the actual definition mentioned at the beginning of this paragraph is probably better overall. This discussion will concentrate on SDI systems with driplines deeper than 2 inches and this may help limit the discussion to SDI systems that have more similarity in design characteristics and operational properties.

SDI is suitable for a wide variety of horticultural and agronomic crops, and, in many respects is applicable to those crops presently under surface drip irrigation (DI). SDI has 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. SDI has been used primarily for high-valued horticultural crops (fruits, vegetables, and ornamentals), tree crops (nuts and fruits), vineyards, and sugarcane. As system reliability and longevity improved, SDI has begun to be used with lower-valued agronomic crops (cotton, peanuts, and cereal crops). This is primarily because SDI system's longevity has increased to the point that investment costs can now be amortized over longer periods.

Although there are numerous advantages for SDI (Lamm, 2002; Lamm and Camp, 2007) there are also many unique challenges to successful use. The adaptation and adoption of SDI systems into diverse cropping systems are unpredictable and depend on the geographical region, soils and climate conditions, and, to a large extent, on how potential advantages are balanced against potential disadvantages. In addition, cultural differences, traditions, skills, and perceptions can have a large influence on whether SDI will be accepted. SDI requires concentrated and consistent management of both water and nutrients to assure adequate crop performance and is also less forgiving than other irrigation systems (Phene, 1996).

Adoption of SDI in a new region can be hampered by the lack of good information on design, management, maintenance, and crop performance, along with the lack of qualified equipment distributors and installers. A goal of this paper is to discuss some of the unique challenges of SDI as a means of broadening their conceptual understanding so that SDI adoption can be optimized in regions where it is appropriate. A broader conceptual understanding can help the novice SDI system end-users ask the right questions and can help researchers and extension specialists formulate new techniques and strategies to alleviate some of these challenges. Much of this paper summarizes material obtained by the author in preparing for a recent book chapter concerning SDI (Lamm and Camp, 2007). Topics will include the challenges associated with design and installation, soil types and characteristics, cultural practices, differential crop response, maintenance, system monitoring and operation.

Challenges with SDI System Design and Installation

Suitability and Site Selection

Although SDI is technically suitable for a vast number of crops in many diverse regions, it may not be the best irrigation system choice for specific situations. Water managers, system designers and producers should not automatically assume that SDI can be successfully adopted. Suitability and site considerations have been the subject of several recent publications that can aid in making appropriate decisions (Lamm et al., 2003; Dukes, et al.; 2005; Grabow et al., 2005; Burt and Styles, 2007; Lamm and Camp, 2007; Rogers and Lamm, 2009).

Subsurface drip irrigation systems may have a higher initial investment cost than the typical alternative irrigation system used in many regions. In many instances, the SDI system has no resale value or minimal salvage value. Lenders may require greater equity and more collateral before approving SDI system loans. Such large investments may not be warranted in areas with uncertain water and energy availability, particularly where crop yield and price outlook is poor. SDI systems typically have a shorter design life than alternative irrigation systems, which requires that the annualized depreciation costs must increase to provide for system replacement.

SDI is often a less-developed technology than other types of irrigation systems particularly in regions where growers have little exposure and experience with these systems. Often, turn-key systems are not readily available. In some regions, the lack of contractor capacity can result in less than optimal installation timing during wet periods. Design errors are more difficult to resolve because most of the SDI system is below ground. More components are typically needed for SDI than surface drip irrigation (DI) systems. Soil materials can possibly enter the driplines (soil ingestion) at system shutdown if a vacuum occurs. Air relief/vacuum breaker devices must be installed and be operating correctly to prevent this problem. As with any microirrigation system, zone size and length of run will be limited by system hydraulics. Compression of the dripline due to soil overburden can occur in some soils, causing adverse effects on flow. There are also many possible soil water redistribution issues that affect suitability. Many of the soil factors will be discussed in later sections of this paper. SDI systems are not typically well suited for Site Specific Variable Application (SSVA) because the zone size is to a great extent fixed at installation and may not spatially represent the location needing variable application very well.

Areas with variable or shallow soil overlaying rock may not be suitable for SDI because of shallow or restricted depth. Coarse sands and non-bridging soils may also be unsuitable for SDI. When using thin-walled driplines, the weight of the overburden may collapse or deform the dripline, which will reduce the flowrate. Undulating or rolling topography presents design challenges that may limit SDI suitability because of the added hazard of backsiphoning soil material into the dripline when the system shuts down. SDI installed on cracking and heavy clay soils may cause soil water distribution problems that may limit its use on the crops of the region. This can sometimes be avoided with alternative irrigation systems that apply water to the soil surface. In arid and semiarid regions, the limitations on SDI use for crop establishment and salt leaching are added suitability considerations. Crop establishment with SDI can also be a problem on coarse-textured soils or when short drought periods occur at planting in the more humid regions.

Cropping practices of a region may affect the perceived suitability of SDI. In regions where high-value horticultural, tree, and vine crops are grown, 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. Although many of these negative perceptions can be overcome, growers may be unwilling to change their cultural practices or management (Phene, 1996). Adequate soil water for crop germination with SDI is important in semiarid and arid regions and in other regions prone to drought during crop establishment.

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. Root intrusion from some crops may limit SDI suitability while crop harvest problems might be an SDI concern for other crops. Some of these issues will be discussed in more detail in a later section of this paper concerning Challenges with Differential Crop Response.

Saline water application through SDI may result in adverse salt buildup 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. 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.

Physical Characteristics of SDI Systems, Driplines, and Emitters

Dripline depth

The choice of the appropriate dripline depth is affected by crop, soil, and climate characteristics, anticipated cultural practices, grower experiences and preferences, the water source, and prevalence of pests. Camp (1998) reported in an extensive review of SDI that the placement depth of driplines ranged from 1 to 28 inches. The depth was determined primarily by crop and soil characteristics. In most cases, dripline depth was probably optimized for the local site by using knowledge and experiences about the crop for the soils of the region.

SDI systems for lower-valued commodity crops (fiber, grains, and oilseeds) and perennial crops (trees and grapes) are usually set up exclusively for multiple-year use with driplines installed in the 12 to 20-inch depth range. Most of these crops have extensive root systems that function properly at these greater depths.

Soil hydraulic properties and the emitter discharge affect the amount of upward and downward water movement in the soil and thus are factors in the choice of dripline depth. When surface wetting by the SDI system is not needed for germination or for salinity management, deeper systems can reduce soil water evaporation and weed growth.

Deeper dripline placement will minimize soil water evaporation losses, but this must be balanced with the potential for increased percolation losses, while considering the crop root-zone depth and rooting intensity (Gilley and Allred, 1974; Thomas et al., 1974; Philip, 1991).

Surfacing is an SDI phenomenon in which excessive emitter discharge, coupled with insufficient soil water redistribution, creates or uses an existing preferential flow path to allow free water to reach the soil surface. Surfacing can sometimes be avoided with deeply-placed driplines (See section Challenges with Soil Types and Characteristics), but this is only an acceptable solution when the mismatch of emitter discharge and soil properties is small and the added soil depth provides a larger soil volume for water redistribution.

Soil layering or changes in texture and density within the soil profile affect the choice of dripline depth. Driplines should be installed within a coarse-textured surface soil overlaying fine-textured subsoil so that there is greater lateral movement perpendicular to the driplines. Conversely, when a fine-textured soil overlays a coarse-textured subsoil, the dripline should be installed within the fine-textured soil to prevent excessive deep percolation losses. An excellent discussion of how soil texture and density affect soil water redistribution is provided by Gardner (1979).

The dripline should be deep enough that the anticipated cultural practices can be accommodated without untimely delays, soil compaction, or damaging the SDI system. The grower's depth preference must be considered with respect to rooting characteristics of the crop and the soil's water redistribution properties. Some growers prefer that the soil surface be periodically wetted with SDI as an indicator of system performance, even though this promotes greater soil water evaporation losses and weed germination. Some growers in the Salinas and Santa Maria Valleys of California have abandoned SDI in favor of DI for broccoli, cauliflower, celery, and lettuce rather than contend with harvesting issues associated with buried driplines (Burt and Styles, 1999). Pests such as rodents and insects are often more troublesome at the shallow dripline depths.

Saline waters and biological effluents often impact the choice of a dripline depth. The application of saline water at shallow dripline depths may create a zone of high salinity near or at the soil surface that is detrimental to seedling and transplant growth and establishment. In arid areas where precipitation is insufficient, it may become necessary to leach this zone with sprinkler irrigation. Some growers have used tillage to scrape off or displace this salinity zone before each planting. The dripline depth for application of biological effluents is chosen so that the pathogen exposure paths at the soil surface are reduced, but with a depth that would not prevent normal biological decay.

The use of SDI in regions subjected to freezing and frozen soils adds an additional dripline depth consideration. Deeply placed SDI systems are less likely to freeze, but supporting system components (e.g., valves and filters) sometimes may freeze and limit operation (Converse, 2003). Snow cover can insulate and protect the SDI system from very cold air temperatures. SDI was durable enough to withstand winters in the U. S. Northern Great Plains when temperature at the 12-inch dripline depth was below freezing for 90 consecutive days in 1993-94 and the frost depth reached 36 inches (Steele et al., 1996).

Greater dripline depths can limit evaporation and decrease rainfall runoff, but may cause greater percolation of applied water or reduce beneficial transpiration in shallow-rooted crops. These conditions can reduce the effectiveness of applied water and thus application efficiency. The interactions between the soil water budget components with dripline depth are also closely affected by soil type and crop characteristics. The unsuccessful adoption of SDI in many regions is caused by the improper balancing of these interrelationships or by the lack of understanding of the need for the proper balance.

Dripline spacing

Crop row or bed spacing is usually set by cultural practices for a given crop in a given region and by planting and harvesting equipment specifications. 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., 1995). 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.

Dripline spacing is usually one dripline per row/bed or an alternate row/bed middle pattern with one dripline per bed or between two rows. SDI systems on some widely spaced tree crops may have multiple driplines between tree rows to wet a larger portion of the canopy floor. In a review of SDI, Camp (1998) reported dripline spacing from 0.8 to 16 ft, with narrow spacing used primarily for turfgrass and wide spacing often used for vegetable, tree, or vine crops on beds. The soil and crop rooting characteristics affect the required lateral spacing, but there is general agreement that the alternate row/bed dripline spacing (about 5 ft) is adequate for most of the deeper-rooted agronomic crops on medium- to heavy-textured soils. Wider dripline spacing may be suitable in soils with layering, allowing increased horizontal soil water redistribution above the soil layer, and in regions that are less dependent on irrigation for crop production. Closer dripline spacing has been suggested for high-valued crops on sandy soils (Phene and Sanders, 1976) and/or in arid areas to ensure adequate salinity management and consistent crop yield and quality (Devitt and Miller, 1988).

Emitter spacing and discharge

Emitter spacings ranging from 4 to 30 inches are readily available from the manufacturers, and other spacings can be made to meet a specific application. Increasing the emitter spacing can be used as a technique to allow larger emitter passageways less subject to clogging, to allow for economical use of emitters that are more expensive to manufacture, or to allow longer length of run or increased zone size by decreasing the dripline nominal flowrate per unit length. The rationale for increased emitter spacing must be weighed against the need to maintain adequate water distribution within the root zone. An excellent conceptual discussion of the need to consider the extent of crop rooting in irrigation design is presented by Seginer (1979). Although the effective uniformity of microirrigation experienced by the crop is high, the actual detailed uniformity within the soil may be quite low. It should be noted that using the widest possible emitter spacing consistent with good water redistribution can cause significant problems when emitters become clogged. However under full irrigation, emitter spacings as great as 4 ft have not proven detrimental to field corn production on the deep silt loam soils of semi-arid Kansas (Arbat et al., 2009).

Wide ranges of emitter discharge are available from the various dripline manufacturers. The evapotranspiration (ETc) needs of the crop generally have little influence on the choice of emitter discharge because most emitter discharges at typical emitter and dripline spacings have application rates well in excess of peak reference ETc. Some designers prefer emitters with greater discharge because they are less subject to clogging and allow more flexibility in scheduling irrigation. When emitters with greater flowrates are chosen, the length of run may need to be reduced to maintain good uniformity and to allow for adequate flushing within the maximum allowable operating pressure. In addition, the zone size may need to be reduced to keep the total system flowrate within the constraints of the water supply system. Decreasing the length of run or the zone area increases the cost of both installation and operation. The choice of emitter discharge must take into account the soil hydraulic properties to avoid backpressure on the emitters and surfacing of water.

Dripline length and diameter

A guiding principle in microirrigation design is to obtain and maintain good water application uniformity along the length of the driplines. Dripline and emitter characteristics and hydraulic properties, the system operating pressure, and the land slope are the major governing factors controlling the hydraulic design. When soil compaction is likely to occur, dripline lengths may need to be reduced to maintain the initial system uniformity. These factors determine the acceptable dripline lengths for the SDI system with respect to the field size and shape and grower preferences. Longer driplines may result in a less expensive system to install and operate, which is of great importance to those growers using SDI on lower-valued crops. Longer dripline length is less important to growers of higher-valued crops, however, and may limit the grower when applying precise water and chemical applications to remediate site-specific crop and soil problems or to elicit a site-specific crop response.

Longer driplines with higher uniformity can be designed by increasing the dripline diameter while holding the emitter discharge constant (Fig. 1). This design technique is popular for larger SDI systems used on the lower-valued commodity crops (fiber, grains and oilseeds) because it can help to reduce installation costs through fewer pipelines, controls, and trenches. This design technique is not without its concerns, however, because larger dripline diameters increase the propagation time of applied chemicals, and dripline flushing flowrates can become quite large.

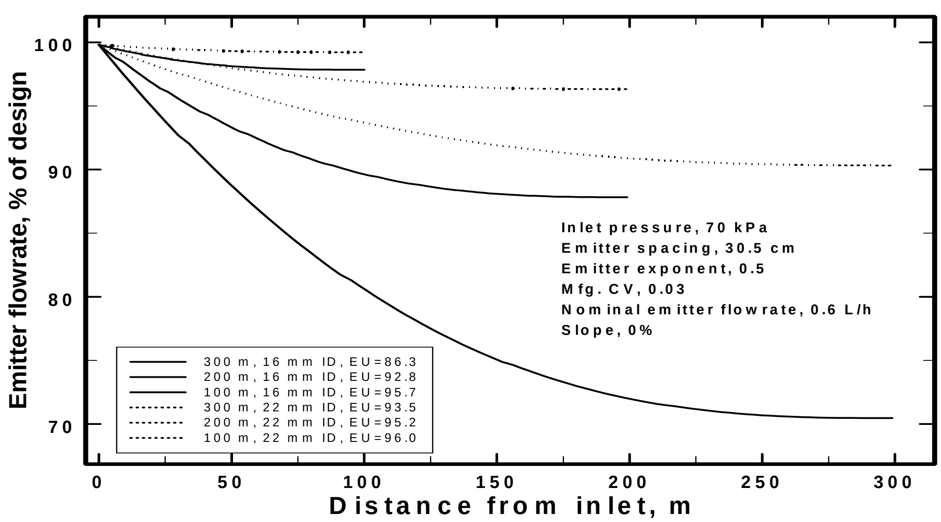

Figure 1. Calculated emitter discharge and emission uniformity (EU) as affected by dripline length and inside diameter. Results for hypothetical dripline calculated with software from Roberts Irrigation Products[1] (2003).

Limited research has been conducted in evaluating the injection of gases into the soil profile with SDI. Gases might be injected for fumigation, aeration, fertilization, or even to modify soil temperature. Compressible gas and gaseous water mixture flow and distribution through the SDI system are much different than standard water flow and distribution (e.g., changes in flow characteristics due to viscosity and friction losses; gaseous mixtures changing concentrations along the length of dripline). This may place design and operational limits on the use of gas injection on larger and longer SDI systems.

SDI use is increasing in lower-valued commodity crops, such as cotton and corn, and as a result, there is an increased need for lower-cost systems with reliable designs and installations. Manufacturers have responded to this need by providing larger-diameter driplines and driplines with lower nominal flowrates, so that longer lengths of run and larger zone sizes can be designed with high uniformity. These larger-diameter driplines, although costing more per unit length, can often result in a less expensive installation through reduction of trenching and system controls. Dripline diameters up to 1.375 inches are now available and are often used in the larger fields to decrease the number of required zones and obstructions posed by additional valve boxes. Each SDI system design is different, however, and the grower should not automatically choose the larger dripline diameter. Larger driplines require longer fill and drain times, which can adversely affect water and chemical application uniformity and redistribution within the soil. Chemigation travel times for the larger-diameter driplines can exceed the period of the planned irrigation event on coarse-textured soils and thus lead to leaching and/or improper chemical application. The nominal dripline flowrate can be reduced by reducing the emitter discharge or by increasing the emitter spacing. Physical limitations exist on reducing emitter discharge because smaller passageways are more easily clogged. There also are limitations on increasing the emitter spacing related to adequately supplying the crop its water needs. Driplines with lower emitter discharges of 0.13 to 0.24 gal/h and larger emitter spacing of 12 to 24 inches are economically attractive (reduced design and installation costs) on deeper, medium-textured soils for crops with extensive root systems.

SDI system component issues

The wall thickness of SDI driplines is often greater than for DI because of the added risk of dripline damage during installation and because the SDI system is usually planned to have an extended, multiple-year life. In situations where soil compaction or soil overburden may cause dripline deformation, thick-walled tubing (hard hose) may be selected. Thicker-walled products allow higher maximum dripline pressures that can be used to open partly collapsed driplines caused by soil compaction or overburden, or to increase flow of chemically treated water through partly clogged emitters. In addition, there have been anecdotal reports of greater insect damage to driplines with thinner walls. The thin-walled, collapsible driplines (commonly referred to as drip tapes in the United States) also are used extensively in SDI. In most cases for SDI, wall thicknesses of 254 to 635 µm are selected instead of the thinner-walled models often chosen for single-year use in DI. Some concerns have been raised on waste plastic product (driplines) in the subsoil when the SDI system is abandoned.

System component reliability, durability, and ease of installation and repair become significant quality and maintenance-control concerns when the system is underground, where leaks and other problems are difficult to detect, find, and repair (Lamm et al., 1997b). A multitude of dripline connectors and connection procedures are commercially available. Selection of a connector that properly matches the dripline characteristics with an easy and reliable connection procedure is important for ensuring a successful installation. Because of the variation in individuals' ability to make watertight connections, quality control and assurance are recommended during installation. The connections should be pressure-tested with water to locate leaks before the trenches are backfilled. Thus the pump and filtration system must be operational before SDI installation.

SDI systems require additional components that are either not required or not used to the same extent for other types of microirrigation systems. Flushlines are header or manifold pipelines installed at the distal end of the zone that allow for jointly flushing of a group of driplines. In addition to flushing, the flushline also serves to equalize pressure between driplines during normal operation and to reduce the potential for entry of soil-laden water by providing positive water pressure on both sides of a severed dripline. It should be noted that the flushline allows for the convenient flushing of a group of driplines but does not increase the effectiveness of flushing. Hydraulically, it is more effective to flush a single dripline, and, as a result, flushlines are not typically used on the high-valued perennial crops such as grapes and tree crops. Air/vacuum relief valves are required on all irrigation systems, but are needed to a greater extent on SDI systems to minimize backsiphoning of water into the emitters.

Clogging of emitters by soil ingestion caused by backsiphoning at system shutdown can occur with SDI and does not usually occur with DI. Prevention of soil ingestion in SDI is usually approached through installation of air/vacuum relief valves at the high elevation points in the system and through improved emitter characteristics, such as closing slits or flaps that may provide a “checkvalve” feature at shutdown. Some manufacturers have changed dripline designs in attempts to reduce or eliminate this problem. Continued improvements in emitter design that limit soil ingestion will be an important factor in adoption of SDI on undulating soils, where the addition of sufficient air/vacuum relief valves can be a significant design impediment due to added cost and/or system complexity.

Instances have been reported of soil being trapped under the elastic membrane in pressure-compensating (PC) emitters that results in unregulated flow. PC emitters are sometimes not used for SDI for this reason. Root intrusion can also be a problem for SDI and some manufacturers have responded altering dripline and emitter physical characteristics or through addition of chemical inhibitors

Challenges with Soil Types and Characteristics

Soil Overburden and Compaction Issues

Driplines can be deformed by soil overburden and/or compaction that will decrease flowrates and reduce system uniformity. This is especially true for thin-walled driplines. Compression of driplines from their normal circular shape into an elliptical shape increases the friction head loss and thus will reduce the flowrate from the design condition (Hills et al., 1989). The flowrate reduction can become significant when the amount of compression is great (Fig. 2). When soil compaction is likely to occur, dripline lengths may need to be reduced to maintain the initial system uniformity. SDI system operation for extended periods (Hills et al., 1989) and initiation of the system after large precipitation wetting events can remediate some of the dripline compression problems by reducing soil compaction in the immediate vicinity of the dripline. Soil compaction can be avoided by limiting mechanized field operations when soil water conditions are most conducive to compaction (i.e., usually slightly drier than field capacity for many soils). In bridging soils, deeply placed driplines are usually less susceptible to compression by soil compaction. However, in nonbridging soils, soil overburden at deeper depths is a concern for SDI systems. The problem of overburden in sandy soils may require the use of heavy-walled, compression-resistant driplines (hard hose) instead of the less expensive thin-walled, collapsible driplines used in many systems.

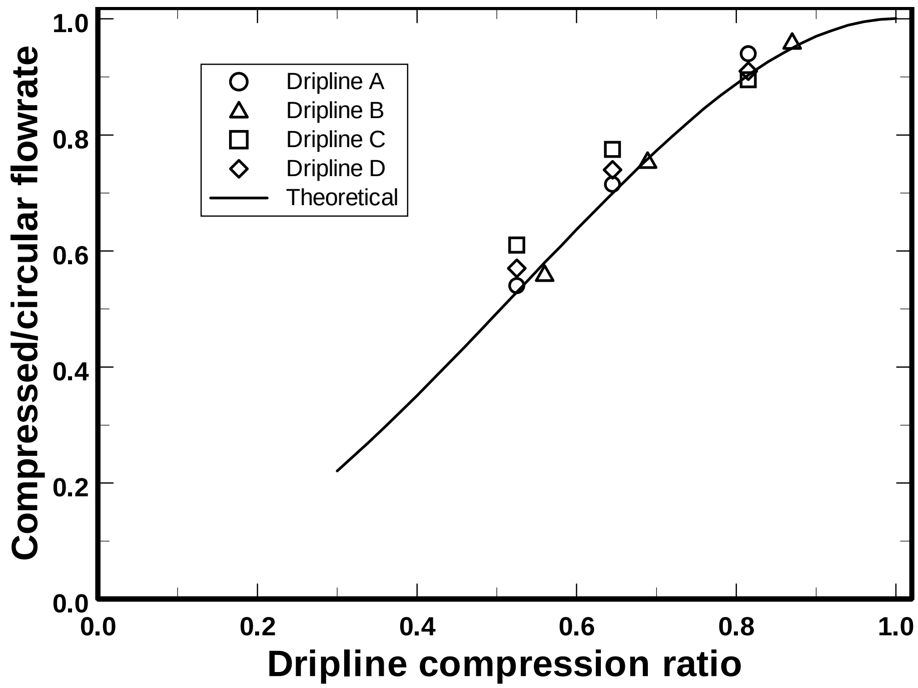

Figure 2. Decrease in flowrate resulting from deforming a circular cross-section into an elliptical cross-section. The dripline compression ratio is equal to the minor axis of the elliptical (compressed) dripline divided by the original circular dripline diameter. The solid line represents the theoretical relationship, and the data points are for the four driplines tested. After Hills et al. (1989).

Reduced Upward Water Movement and Seed Germination Concerns

Adequate soil water for crop germination with SDI is important in semiarid and arid regions and in other regions prone to drought during crop establishment. Germination may become a problem depending on the installation depth and soil properties. This may be particularly troublesome on soils with vertical cracking or for coarse-textured soils and shallowly planted seeds. Salt accumulation may be increased above the dripline, thus creating a salinity hazard for the emerging seedlings or small transplants. Dripline depth is important in affecting the surface and near-surface soil water conditions with shallower dripline depths providing wetter conditions. Tillage and planting practices can sometimes be used to prevent or avoid dry soil conditions for 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 can be removed to the traffic furrow, thus exposing wetter and firmer soils for crop establishment. Using emitters with a greater discharge rate also can improve soil water conditions for crop establishment but may negatively affect system design and installation costs and exacerbate soil water surfacing. Pulsing the SDI system, which involves applying small increments of water multiple times per day rather than applying a larger amount for a longer duration, has been advocated as a procedure to improve surface and near-surface wetting for crop establishment. Although considerable research and theory to support this technique for improved wetting patterns are available for DI (Zur, 1976; Levin and van Rooyen, 1977; Levin et al., 1979), little research and few operational guidelines exist for SDI.

Soil/Application Rate Interactions

Water redistribution may be too low on coarse-textured soils, resulting in a limited wetted zone. This particularly may be a problem for tree crops with their extensive root system which may necessitate selection of an alternative irrigation system or installation of more driplines for each crop row.

In some situations, the SDI emitter discharge is greater than the saturated hydraulic conductivity of the soil in the immediate vicinity of the emitter leading to backpressure on the emitter which can cause irrigation uniformity problems that can have both an irrigation system aspect and a soil water redistribution aspect. Application of biological effluents through the SDI system may exacerbate these problems by blocking soil pores or through chemical changes to soil properties. SDI system uniformity can be reduced when the soil is unable to redistribute water away from the emitter fast enough to prevent backpressure on the emitter. Reductions in emitter discharge of 9.5, 17.5, and 29.6% due to backpressure were calculated for design emitter discharges of 0.26, 0.53, and 1.06 gal/h, respectively, for the hydraulic properties of a sandy loam in Israel (Warrick and Shani, 1996). This resulted in corresponding Christiansen's uniformity (UC) values of 95, 91, and 85 for the SDI system. When the emitter discharge increases or the soil hydraulic conductivity decreases, the pressure head increases around the emitter and reduces the emitter discharge, depending on the severity of the mismatch between the emitter and soil characteristics. Soil type, emitter discharge, presence of cavities around the emitter, and SDI system hydraulic properties were listed by Shani et al. (1996) as the controlling factors for the existence of backpressure and the subsequent emitter flow reduction. In a preliminary study, they reported emitter discharge reductions of as much as 50% were attributable to backpressure. Modeling procedures to account for the effect of backpressure on emitter discharge have been developed by Lazarovitch et al. (2005).

Soil water redistribution may be adversely affected by the backpressure phenomenon. The applied water from the emitter discharged with a pressure greater than atmospheric may also seek a path of least resistance to release its energy. Sometimes the path of least resistance is upwards and the water will travel to the soil surface causing differential soil water redistribution, wet spots that may interrupt farming operations, increased soil water evaporation, and possibly irrigation runoff. This "surfacing" phenomenon also may be directly associated with a "chimney effect" in which small, fine soil particles are carried to the surface in the preferential flow path or macropore. The sorting of soil particles and deposition into the walls of the chimney will further reinforce the preferential flow path and surfacing may become worse. These depositional crusts that are formed within the soil profile can have hydraulic conductivities that are reduced by 2 to 3 orders of magnitude (Shainberg and Singer, 1986; Southard et al., 1988). The chimney can be disrupted by tillage, but will often reappear because the flow channel still exists in the region around the emitter which was undisturbed by tillage. The surfacing and chimney effects are somewhat analogous to volcanic activity (Zimmer et al., 1988), and the point where free water exits the soil has even been called a caldera (Fig. 3). Surfacing can be a significant problem on some soil types and is particularly troublesome when it occurs in alfalfa fields resulting in wet spots at harvest (Hutmacher et al., 1992; McGill, 1993). The preferential flow path or macropore does not necessarily exist before installation of SDI. Rather, the macropore can be caused by the SDI-applied water forcing an outlet (Battam et al., 2002). The extent of surfacing is dependent on soil type, dripline depth, and emitter discharge (Zimmer et al., 1988; Shani et. al., 1996; Battam et al., 2002). Decreasing the emitter spacing will allow reduced emitter discharges, while maintaining the SDI system design flowrate and thus may be a primary method of preventing surfacing problems. Using shorter-duration irrigation events (pulsing) may reduce the amount and magnitude of unwanted surface water problems, but may not prevent surfacing (Battam et al., 2002). They suggested that a partial remedy to an existing surfacing problem would be to reduce operating pressures, thus reducing emitter discharge rates.

Figure 3. Caldera resulting from surfacing of water from an SDI emitter in California. Photo courtesy of F. R. Lamm, Kansas State University.

Challenges with Cultural Practices

Tillage and Harvesting Issues

Tillage and other cultural practices can also damage driplines, resulting in leaks that reduce system uniformity. Primary and secondary tillage operations may be limited by dripline placement and depth. SDI systems should be installed at the specified dripline depth uniformly throughout the field so that tillage and cultural practices can be planned to accommodate this depth without causing damage. Because SDI systems are fixed spatially, it is difficult to accommodate crops of different row spacing. Some crops may require very close dripline spacing that may be economically impractical. Additional caution must be taken at the time of annual row-crop planting to ensure that crop orientation and spacing are appropriately matched to dripline location. Ayars et al. (1995) reported an instance where several hundred feet of dripline had to be replaced because the bedding operation damaged dripline that had been improperly placed (inconsistent depth and location). For SDI driplines installed at an 3 inch depth, Chase (1985) reported damage by planting and weeding operations. Shallow driplines can also be damaged by wheel traffic during harvesting in wet soil conditions. Heavy alfalfa-harvesting equipment damaged SDI driplines at a 4-inch depth in Hawaii (Bui and Osgood, 1990), whereas driplines at 14 inches were not damaged. Cultural operations with tractors and harvesters during wet soil conditions may damage driplines in shallow SDI installations, especially if installed in the inter-row area where wheel traffic occurs.

Salinity and Irrigation Management Interactions

Both temporal and spatial soil salinity and water distributions can be important for SDI. Upward water movement from subsurface driplines can create a highly saline zone above the emitters that can be toxic to transplants and seedlings. The same level of salinity at this depth may be of little consequence to an established crop provided that the saline zone does not move into the active root zone. Growers may remediate the problem of salinity in the seeding or transplanting zone by dormant season leaching with precipitation or sprinkler irrigation (Nelson and Davis, 1974). Another method is to build up the crop bed to a greater height than normal, move the salts into this higher peak through irrigation, and then remove the salt accumulation in the peak location through tillage before planting (Hanson and Bendixen, 1993). The management of crop location with respect to dripline location can be important for even moderately saline waters with SDI systems that are used for multiple years unless periodic leaching is provided. Root activity was limited to the wetted soil volume for drip-irrigated tomato and peanut on a sandy soil, but the rooting patterns were different for fresh and saline water (Ben-Asher and Silberbush, 1992). When freshwater was used, a relatively high root density occurred around the periphery of the wetted volume, but with saline water limited root activity existed at the periphery. Most root activity occurred in the leached zone beneath the emitter.

Nutrient Management and Availability

The combined management of water and nutrients is one of the most significant advantages of SDI. Water and nutrients can be supplied in optimum amounts to the most active part of the crop root zone, with timing appropriate for maximum plant response, while minimizing the potential for nutrient leaching. However, smaller root zones can make irrigation and fertilization critical issues from both timing and quantity perspectives. The restricted volume may not be sufficient to supply water to the plant so that diurnal crop water stresses can be avoided. Application of nutrients through the SDI system may be required for optimum yields. Application of micronutrients may also become more critical because the smaller soil volume is depleted of these nutrients in a shorter time.

Fertilizer applications for most crops are most effective when applied at the latest possible date compatible with quick uptake by the plant. The key point is providing the fertilizer in a readily available form in the presence of the crop root system. Subsurface drip irrigation can effectively manage the placement and availability of both soil mobile and immobile nutrients. Phosphorus fertigation with SDI can increase plant nutrient uptake, root growth and crop yield. Application of P through SDI accomplishes more than just placing the P at the center of the crop root zone. Continuous P fertigation allows uptake of this relatively immobile nutrient through mass flow to the plant roots rather than just the roots growing and coming in contact with fixed P within the soil profile (Bar-Yosef, 1999). However, care must be exercised when applying P through microirrigation systems to avoid emitter clogging. This requires using appropriate P formulation and careful attention to water chemistry. Similarly, nitrogen fertigation with SDI can also be beneficial in plant nutrient uptake, root growth or crop yield, and environmental protection. Some forms of N are readily leachable, so SDI can be a good tool for timely applications with precise placement in the crop root zone. Plants are capable of direct uptake of both ammonium- and nitrate-N. Ammonium-N is held on the cation exchange complex and is relatively unleachable, whereas nitrate-N is free to move with the soil water solution. The nitrogen fertilizer solution urea-ammonium nitrate (UAN, 32-0-0) is not only very water soluble for SDI injection (reduced emitter clogging hazard), but also contains approximately 25% nitrate-N, 25% ammonium-N, and 50% urea-N (reduced in the first step to ammonium-N). Subsurface drip irrigation of water containing UAN (32-0-0) supplies both the readily absorbed nitrate-N and the less mobile ammonium-N, which can be absorbed directly by the plant or microbially transformed to nitrate-N. Combined management of irrigation and anticipated rainfall has long been a necessary tool to manage nitrogen fertilization on sandy soils. An untimely rainfall event, coupled with a fully recharged soil profile, can lead to the loss of a significant portion of the soil N. Under dry climatic conditions it may become necessary to apply at least a portion of the required crop N through the SDI system to prevent N applied to the soil surface from becoming positionally unavailable to the crop because the active root zone is deeper in the soil nearer the point of water application (Fig 4).

Figure 4. Subsurface drip-irrigated field corn experiencing nitrogen stress due to dry surface soil conditions despite having abundant nitrogen reserves in the soil surface layers from surface application of N. The SDI driplines in this field were installed at a depth of 16 to 18 inches. The situation was later remedied by application of some N through the SDI system.

Challenges with Differential Crop Response

Some crops may perform better under SDI than others and some crops may present challenges to SDI system maintenance. For example, some crops such as sweet potato, celery, asparagus and permanent crops that have a long period when irrigation is minimal or terminated, may exhibit high root intrusion into SDI emitters (Burt and Styles, 1999). Although peanuts are successfully grown with SDI in some regions (Sorenson et al., 2001), the plant process of pegging can be inhibited in arid regions and in cracking soils (Howell, 2001). 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).

While crop transpiration for a well-watered crop does not vary across irrigation systems, differences can exist in the ability of alternative irrigation systems to provide a consistently well-watered condition that matches plant growth and the economic yield formation needs of the crop. In essence, the extent to which the conditions match a well-watered condition could differ spatially within the crop root profile and also could differ temporally on diel or longer timescales.

The presence of a consistently and adequately wetted root zone can be especially important for crops that develop yield below the soil surface. Increased soil water availability and reduced soil strength on soils wetted by SDI were contributing factors in higher onion yields in India (Abrol and Dixit, 1972). Potato yield was increased 27% with SDI over sprinkler irrigation while reducing irrigation needs by 29%, provided there were driplines in each crop row (DeTar et al., 1996). Their results indicated that very little water would be wasted using a high frequency, every-row SDI system and that the system could closely match the actual potato transpiration needs. Nutrient availability, mobility, and plant uptake can also be enhanced under the SDI-controlled wetted volume near the center of the crop root zone (Bar-Yosef, 1999). Conversely, when the controlled wetted volume is not matched well to the crop root zone, SDI can be a poor irrigation method. 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.

Greater corn grain yields were reported for SDI in three normal to wetter years in Kansas (Fig. 5), but LEPA (low energy precision application) 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 15 bu/acre) were associated with greater kernels/ear as compared to SDI (534 vs. 493 kernels/ear) in the extreme drought years. Greater SDI yields (approximately 15 bu/acre) 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.

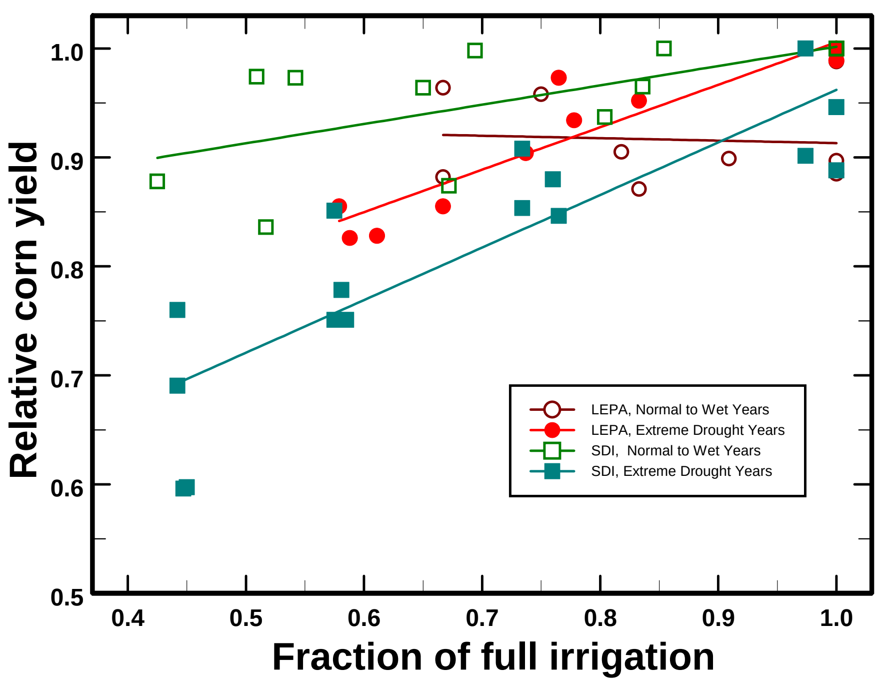

Figure 5. Corn grain yield as affected by irrigation system type (LEPA sprinkler and SDI) for various irrigation regimes in normal to wetter years and extreme drought years, KSU Northwest Research-Extension Center, Colby, Kansas.

Challenges with System Maintenance

Filtration and Dripline Flushing

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 surface microirrigation 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.

Accumulated sediments must be periodically flushed from the SDI system. In many instances, the assurance that adequate water flushing velocities can be obtained throughout the proposed SDI system will be the controlling factor in the sizing of irrigation zones, pipelines, driplines, and emitter discharges (Burt and Styles, 1999). The flushing requirement and associated components add considerable complexity and cost to the SDI system, but are integral to a successful system. The ASABE recommends a minimum flushing velocity of 1 ft/s (ASAE EP-405) but some publications recommend greater flushing velocities for SDI because it is below ground. However, it must be noted that greater flushing velocities will increase system cost and reduce zone size. Flushing velocities greater than 1 ft /s did not have large effects on emitter clogging or emitter discharge in an SDI study in Kansas (Puig-Bargués et al., 2009).

Mechanical and Pest Leaks

Mechanical (system installation and crop tillage) and pest (burrowing mammals and insects) damage can cause leaks that reduce system uniformity when they are not located and repaired. Minor leaks on deeper SDI systems may not wet the soil surface, and may be discovered only by a chance observance of differential plant growth along the damaged dripline during the growing season. Large leaks are easier to locate than small ones, particularly when no crop is present. Many growers routinely start their SDI system before the cropping season to inspect for leaks and make repairs. Holes in the dripline can allow soil and debris to enter the dripline, decreasing the flow in the larger dripline chamber and possibly clogging other emitters downstream. Successful repairs and/or remediation depend on the early detection of problems. Fully or severely clogged emitters are much more difficult to remediate than partially clogged emitters (Ravina et al., 1992). Rodent damage can also be reduced when the problem is recognized early, and steps are taken to reduce rodent habitat and activity in the field.

Burrowing mammals, principally of the rodent family, can cause extensive leaks that reduce system uniformity. Most rodents avoid digging into wet soil, so dripline leaks presumably are not caused by the animals looking for water. Rather, rodents must gnaw on hard materials, such as plastic, to wear down their continuously growing teeth. 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. Isolated patches of residue within a barren surrounding landscape will provide an “oasis” effect conducive to rodent establishment. After the smaller rodents become established, other burrowing predators such as badgers can move into the field, further exacerbating the damage. Caustic, odoriferous, pungent, and unpalatable chemical materials have been applied through SDI systems in attempts to reduce rodent damage, but none of these trials has obtained adequate control. Periodic wetting of the soil during the dormant period has been suggested as a possible means of reducing rodent damage. Deeper SDI depths (18 inches 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 12 inches (Cline et. al., 1982).

Burrowing insects can cause dripline leaks that decrease system uniformity. Several incidents of wireworm damage to SDI systems have been reported in the United States. These reports indicated that the damage is most often associated with the initial SDI system installation period and with a delay in wetting the soil after installation. Some growers irrigate immediately after installation, and others have injected fumigants and insecticides to prevent wireworm damage (Burt and Styles 1999). The use of insecticides through SDI systems to control insects that cause leaks is a controversial environmental practice because of possible grower health hazard when repairing any remaining leaks. Growers should always read and carefully follow the pesticide label and precautions. Wireworm activity is usually greatest at the 8 to 14 inch depth (Bryson, 1929), so deeper SDI system installation may help to prevent wireworm damage.

Root Intrusion and Root Pinching

Root intrusion and root pinching of the dripline are unique problems to SDI that can reduce system uniformity. Although these SDI problems have long been recognized, few published, detailed research studies are available. In a literature review of SDI, Camp (1998) cited only 4 of 61 reports that provided management guidelines discussing root intrusion.

Root intrusion tends to be of greater significance under some crops than others. Perennials often present root intrusion problems when roots continue to grow and utilize some water in winter or semi-dormant periods when irrigation is usually not practiced (Schwankl et al., 1993; Hanson et. al., 1997). Root intrusion can become a serious problem in a very short time (Fig. 6). Bermuda grass has caused serious root intrusion problems in less than one year (Suarez-Rey et. al., 2000).

Coelho and Faria (2003) measured root intrusion of coffee and citrus roots into 14 different emitter models placed in containers. Although all tested emitters experienced root intrusion under the harsh conditions of this container study, there were differences in the overall effect on flowrate and variability. They concluded that nonpressure-compensating emitters performed better than pressure-compensating emitters. Pressure-compensating emitters tended to be unstable, initially increasing, and then decreasing the average flowrate when the emitter became clogged with root and soil particles. Nonpressure-compensating emitters were stable, gradually decreasing the average flowrate as roots and soil particles began to clog the emitter. Ingestion of soil was correlated with increased root intrusion. Emitters that undergo gradual flowrate reduction display more advance warning to the grower, who can then alter irrigation management or use chemical methods to prevent or remediate the root-intrusion problem. Root intrusion may disturb or distort the shape of the elastic membrane on pressure-compensating emitters and thus exacerbate flowrate variations. They also noted that root intrusion was greatest under dry conditions as listed in numerous publications (Schwankl et al., 1993; Hanson et al., 1997; Burt and Styles, 1999; Van der Gulik, 1999). Most crop roots do not grow into saturated soils. Consequently, frequent SDI can create a small saturated zone around the emitter that will deter root intrusion. Celery is an exception to this rule, and thus some growers prefer DI or have used chemicals to prevent root intrusion (Schwankl et al., 1993; Hanson et al., 1997). Coelho and Faria (2003) concluded that there was no preferential growth toward the emitter orifice within the wetted soil volume and that root intrusion was just the result of random exploration. However, the ingestion of soil was correlated with increased root intrusion which may lead to capillary formation directing the hair roots towards the emitter opening.

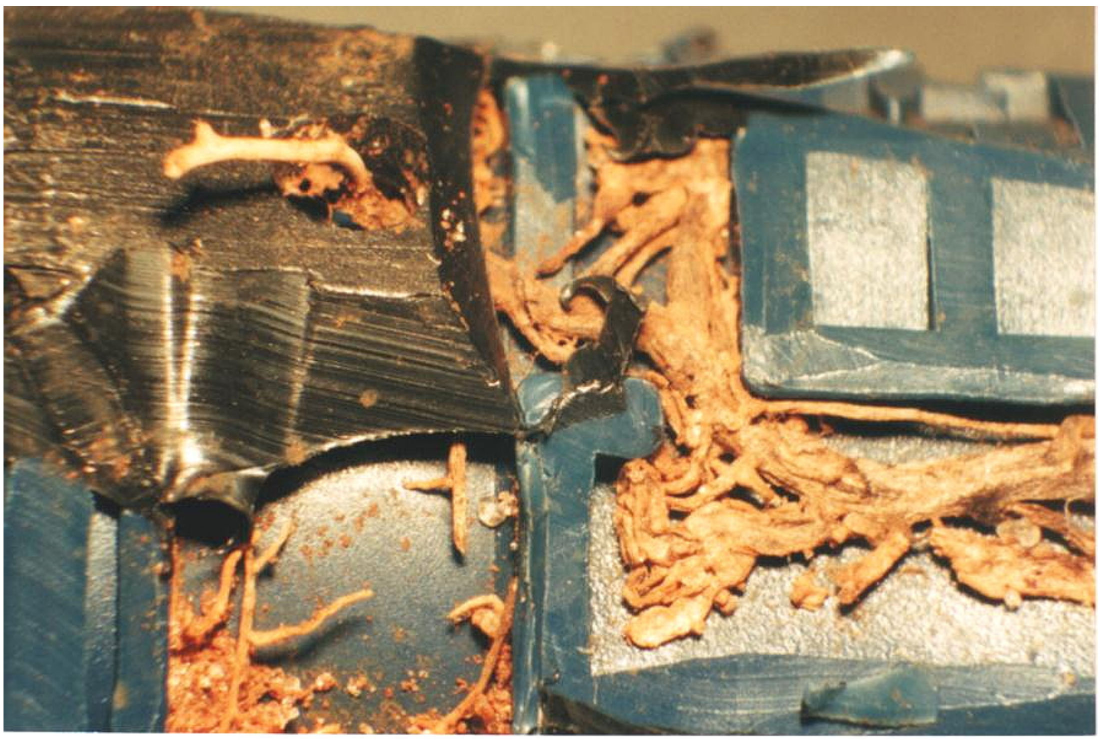

Figure 6. Single coffee plant root entering an emitter can enlarge into a large root mass once inside the emitter and dripline. Photo courtesy of Rubens Duarte Coelho, University of Sao Paulo, ESALQ / Brazil.

The extent of root intrusion varies with different dripline and emitter construction techniques (Bui, 1990). Manufacturers that still use seamed construction have tended to discontinue placing the emitter orifices in the dripline seam because this has been noted as a common root path, once it is located by random root exploration (Schwankl et al., 1993). Manufacturers are marketing a variety of emitter design techniques to avoid root intrusion, such as closing flaps, closing slits, raised protrusions that deflect roots, or oversized water outlets that protect the much smaller emitter orifices below.

Chemical protection of the emitter with herbicide (trifluralin) is another good method of preventing root intrusion. Ruskin and Ferguson (1998) discussed the three primary trifluralin herbicide methods in which the herbicide is injected directly into the irrigation water, incorporated into the emitter at manufacturing, or incorporated into the filter components. Trifluralin acts by stopping cell growth as the root tip encounters the herbicide, but does not kill the plant when properly used for root intrusion (Zoldoske, 1999). Careful and safe use of these herbicide methods according to label instructions is necessary to protect the environment from contamination while attempting to reduce the root-intrusion hazard. The use of acids, acid-based fertilizers, and chlorine may also help to prevent root intrusion or help to remediate partially clogged emitters by oxidizing the roots (Schwankl et al., 1993; Burt, 1995; Hanson et al., 1997; Ayars et al., 1999; Burt and Styles, 1999; Van der Gulik, 1999).

Tree and grape vine roots can grow around and pinch SDI driplines, which either greatly reduces or stops flow in the dripline (Fig 7). This phenomenon has reduced the effectiveness of some SDI systems in California (Burt and Styles, 1999).

Figure 7. Subsurface dripline pinched by peach tree root in California, USA. Photo courtesy of T. Trout, USDA-ARS, Parlier, California.

Challenges with System Monitoring and Operation

Emitter discharge can be affected by clogging (internally from physical, chemical, or biological hazards or externally from soil ingestion caused by backsiphoning), root intrusion, root pinching of the dripline, leaks caused by mechanical or pest damage, soil overburden and/or compaction, soil hydraulic conductivity, and related parameters. Qualitative information about irrigation system uniformity can be continually observed from surface wetting with DI, but this is not true for SDI. Water applications with SDI may be essentially invisible so that it is more difficult to evaluate system operation and application uniformity. There have been cases where producers revert to DI because of the uncertainty of SDI system performance or have intentionally overirrigated with SDI so that they can verify system operation (Fig. 8).

Figure 8. Example of overirrigation of almonds with SDI (right tree line) and the resulting dampening of soil and weed establishment, so that the grower was assured of SDI system operation. A better solution would have been to carefully monitor flowmeters and pressure gauges for the SDI system. Photo courtesy of L. Schwankl, University of California-Davis.

System mismanagement can lead to underirrigation, with reduced crop yield and quality, or overirrigation, with poor soil aeration and deep percolation problems. Careful monitoring of system flowmeters and pressure gauges is required to determine that the system is operating properly. Record keeping is an important aspect in monitoring and ensuring the long-term performance of SDI systems because there are fewer easily observable indicators of performance than with DI. Flowmeters, pressure gauges, and other system operational sensors (e.g., automated backflush controllers, soil water sensors) are used to monitor SDI system operation and performance. Baseline flowrates and pressures for each irrigation zone should be determined at the initiation of new SDI systems. A deviation from these flowrate and pressure baselines, which occurs either abruptly or gradually as part of a trend, is a signal to the grower that a problem (clogging, root intrusion, or a leak) is occurring. An example of how good records can be used to diagnose hypothetical SDI problems can be found in any of the three following references (Lamm and Camp, 2007; Lamm and Rogers, 2009; Rogers and Lamm, 2009).

The volume of soil wetted by the emitter may be too limited on coarse-textured soils and system capacity and system reliability can be extremely critical issues because there is less ability to buffer and overcome insufficient irrigation capacity or system breakdown.

Conclusion

Subsurface drip irrigation can be adapted to a wide variety of cropping systems in many diverse regions. The success of SDI depends on water managers, designers, equipment distributors, irrigation consultants and the end-user in understanding the concepts and managing some of the unique challenges it presents. In some cases, alternative irrigation systems can be a much better choice for the enduser when these challenges are difficult to handle.

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[1] Mention of tradenames is for informational purposes only and does not constitute endorsement by the authors or by the institutions they serve.

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