Subsurface Drip Irrigation: A Review

C. R. Camp

Abstract. *A comprehensive review of published information on subsurface drip irrigation was performed to determine the state of the art on the subject. Subsurface drip irrigation has been a part of drip irrigation development in the USA since its beginning about 1960, but interest has escalated since the early 1980s. Yield response for over 30 crops indicated that crop yield for subsurface drip was greater than or equal to that for other irrigation methods, including surface drip, and required less water in most cases. Lateral depths ranged from 0.02 to 0.70 m and lateral spacings ranged from 0.25 to 5.0 m. Several irrigation scheduling techniques, management strategies, crop water requirements, and water use efficiencies were discussed. Injection of nutrients, pesticides, and other chemicals to modify water and soil conditions is an important component of subsurface drip irrigation. Some mathematical models that simulate water movement in subsurface drip systems were included. Uniformity measurements and methods, a limited assessment of root intrusion into emitters, and estimates of overall system longevity were also discussed.*

Sufficient information exists to provide general guidance with regard to design, installation, and management of subsurface drip irrigation systems. A significant body of information is available to assist in determining relative advantages and disadvantages of this technology in comparison with other irrigation types. Subsurface drip provides a more efficient delivery system if water and nutrient applications are managed properly. Waste water application, especially for turf and landscape plants, offers great potential. Profitability and economic aspects have not been determined conclusively and will depend greatly on local conditions and constraints, especially availability and cost of water.
Keywords. *Subsurface trickle irrigation, Microirrigation, Buried drip irrigation, Consumptive use, Evapotranspiration, Water use efficiency, Fertigation, Irrigation scheduling.*

The purpose of this review was to collect information related to subsurface drip irrigation into a characterization reflecting current knowledge. Such a characterization has not been published. Howell et al. (1980) included a section on subsurface drip irrigation in their overall discussion of trends in drip irrigation. Bucks et al. (1982) provided a brief discussion of subsurface drip in their review of drip irrigation. Likewise, Bucks and Davis (1986) discussed it in a portion of their history of drip irrigation. Other histories and summaries of research trends have been directed to drip irrigation in general but none specifically to subsurface drip irrigation (Hall, 1985; Bucks, 1995; Phene, 1995b).

In ASAE S526.1 "Soil and Water Terminology" (*ASAE Standards*, 1996), drip irrigation and trickle irrigation are defined equivalently, with drip irrigation being preferred. Subsurface drip irrigation is defined by ASAE as "application of water below the soil surface through emitters, with discharge rates generally in the same range as drip irrigation". This method of water application should not be confused with subirrigation, which is defined by ASAE as "application of irrigation water below the ground surface by raising the water table to within or near the root zone". Other definitions of subsurface drip irrigation require lateral placement below normal tillage depth or at a depth that would ensure lateral survival throughout the growing season, implying some degree of permanence. Because tillage depth often varies with crop and type of culture (e.g., conservation tillage), all drip systems with laterals installed below the soil surface (> 2 cm deep) will be considered in this review. Subsurface drip irrigation has been generally used only for the past 10 to 15 years to describe drip/trickle application equipment installed below the soil surface.

Earlier, the nomenclature was much less consistent. For example, "subirrigation" sometimes referred to both subsurface drip irrigation and subirrigation (water table management) (McNamara, 1970); "subsurface irrigation" might also refer to both (Braud, 1970; Goldberg et al., 1976), but often referred to subsurface drip irrigation (Hanson et al., 1970; Whitney, 1970; Edwards et al., 1970); and "drip/trickle irrigation" could include either surface or subsurface drip/trickle irrigation, or both (Sutton et al., 1985; Tollefson, 1985a,b). The definitions provided by Davis and Nelson (1970a) were similar to the current ASAE definitions except that "subsurface irrigation" was used instead of "subsurface drip irrigation", possibly because few commercial drip applicators were available at that time.

Article was submitted for publication in January 1998; reviewed and approved for publication by the Soil & Water Div. of ASAE in July 1998.

Contribution of the U.S. Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water, and Plant Research Center, Florence, S.C. Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the USDA and does not imply approval of a product to the exclusion of others that may be suitable.

The author is **Carl R. Camp, *ASAE Member Engineer*,** Agricultural Engineer, Coastal Plains Soil, Water, and Plant Research Center, 2611 West Lucas St., Florence, SC 29501-1242; tel: 843-669-5203, ext. 107; fax: 843-669-6970; e-mail camp@florence. ars.usda.gov.

This review includes published literature specific to subsurface drip irrigation. However, much of the published literature for drip irrigation in general will also apply to subsurface drip. Primary emphasis was placed on literature in appropriate scientific journals that reported results of replicated studies. Other literature was included to summarize historical development or to report significant information not otherwise available. In the interest of brevity, multiple references to similar information or results were not included.

Historical Development

In 1920, Charles Lee in California was granted a U.S. Patent for an irrigation tile that included orifices on a raised ridge inside the pipe (Lee, 1920). While the irrigation tiles were intended to be used in connection with drainage tiles, apparently their use was not intended to create a water table, as in subirrigation, but to "moisten the soil around the tile"; hence, this was probably one of the earliest forms of subsurface drip irrigation. Availability of plastic following World War II allowed the development of drip irrigation, initially in Great Britain and possibly other countries, and later in Israel and the USA. Subsurface drip was part of drip irrigation development in the USA, beginning about 1959, especially in California (Davis, 1967) and Hawaii (Vaziri and Gibson, 1972). During the 1960s, laterals were constructed using polyethylene or PVC pipe with holes or slits drilled, punched, or cut into the pipe (Braud, 1970; Hanson et al., 1970; Zetzsche and Newman, 1966), or discrete emitter inserts punched into the pipe (Whitney, 1970). Typically, these systems were operated at low pressures with varying water quality and filtration. Whitney and Lo (1969) evaluated plugging and performance of several emitters, concluding that the plastic insert orifice was the preferred type. By 1970, trial installations on commercial farms and sugar plantations were being installed using a variety of both experimental and commercial emitters and laterals (Davis and Nelson, 1970a,b; Davis and Pugh, 1974; Gibson, 1974; Hanson and Patterson, 1974). These systems were used for a variety of crops including citrus, sugarcane, pineapple, cotton, vegetables, fruits, turfgrass, avocado, sweet corn, and potato (Davis and Nelson, 1970a; Davis and Pugh, 1974; Edwards et al., 1970; Hanson et al., 1970; Hanson and Patterson, 1974; Isobe, 1972; Phene, 1974; Phene and Beale, 1976, 1979; Phene and Sanders, 1976). Most problems were related to poor uniformity, system maintenance, and emitter plugging, which was caused by iron oxide or soil particles.

By the 1970s, equipment for installing subsurface drip systems had been developed (Lanting, 1975). Some equipment, while installing the laterals, either punched holes or inserted plastic emitters in the tubing (Zetzsche and Newman, 1966; Whitney, 1970). About the same time, surface drip irrigation systems, including fertilizer injection equipment, were being developed in Israel (Goldberg and Shmueli, 1970). As commercial drip emitters and tubing became more reliable, surface applications grew at a greater rate than did subsurface applications because of problems with emitter plugging and root intrusion.

In the early 1980s, interest in subsurface drip increased, possibly because of material and equipment cost, improved nutrient management, and lower system cost that resulted from multiple-year use. During the first half of the 1980s, reports included information on lateral depth and spacing, chemical injection via the irrigation system, crop yield, water and filtration requirements, and comparisons with other types of irrigation systems (Bucks et al., 1981; Chase, 1985a; Mitchell, 1981; Plaut et al., 1985; Rose et al., 1982; Sammis, 1980; Wendt et al., 1977). Mitchell and Tilmon (1982) reported that subsurface drip systems had been in use for 10 years in their research program and offered guidelines for design, installation, and management of these systems. Also, Tollefson (1985a,b) reported experiences with subsurface drip irrigation for cotton and wheat on a large commercial farm, which started with a test area in 1979. Interest in subsurface drip irrigation increased greatly after 1985, the period when most reports of replicated research studies have been published. More recently, Zoldoske (1993) and Burt (1995) discussed advantages and possible limitations of subsurface drip, while others report experiences with subsurface drip (Cavanaugh, 1992; Duncan, 1993).

Results

The reported information varied widely in content and scope, especially with regard to crop yield, system parameters, plant and soil measurements, and crop water requirements and efficiencies. For information obtained from field or greenhouse studies involving a crop, specific aspects regarding the system, crop response, and water supply and use were summarized by two broad crop classifications, agronomic or horticultural (tables 1 and 2), and grouped by crop within each table. A third category of information included system design and evaluation, which was summarized separately (table 3). All information is cited in the tables, but summaries and selected references only are discussed.

The agronomic group, which also includes turfgrass and forestry products, contains subsurface drip irrigation information for about 10 different crops. By far, more information was reported for cotton and corn than for other agronomic crops, probably because of their economic importance. Other crops, including sugarcane, peanut, turfgrass, wheat, grain sorghum, alfalfa, and forest products, have received much less attention. The horticultural group includes information for over 20 vegetable, fruit, and vine crops. More information was reported for tomato (both processing and fresh market) than for any other crop in this group. Lettuce was next most popular, followed by peas, sweet corn, melons, potato, cabbage, peas, beans, squash, carrot, onion, broccoli, asparagus, pepper, apple, pear, grape, and others.

Information will be discussed by system or management parameter and function; e.g., lateral depth, irrigation scheduling, system evaluation, and comparison with other irrigation systems, first for agronomic crops and then for horticultural crops. Finally, information regarding system design and evaluation will be discussed.

Comparison with Other Irrigation Systems

Subsurface drip irrigation was compared to other irrigation system types in about half of the reports in the agronomic crops group (table 1). Economic comparisons of

Table 1. Summary of information reported for subsurface drip irrigation systems on agronomic, turf, and forest crops

		Lateral			Scheduling/Delivery										
Crop		Depth (m)	Spacing (m)	Type*	Timing	Amt.	MSW†	Other‡	Water Supply§	Other Irrig. Syst.‖	Fert. Mgt.	Irrig. Water Req.	WUE	Plant Meas.	Environ. Effects
Alfalfa	Bui & Osgood, 1990	0.35	1.5	FT				PE		S					
Alfalfa	Kruse & Israeli, 1987	0.12-0.37	1.5												
Alfalfa	Mead et al., 1993	0.41	1, 2												
Bermudagrass	Devitt & Miller, 1988	0.15	0.61, 0.91, 1.22				NP, T		SL						
Bermudagrass	Gushiken, 1995	0.15-0.30	Var.						WW						X
Corn	Adamsen, 1992	0.35-0.41	0.91	FD					SL	S		X			
Corn	Caldwell et al., 1994	0.40	1.5	FD	X	X	NP						X		X
Corn	Camp et al., 1989	0.30	0.76, 1.52	RT	X		T			SD	X				
Corn	Coelho & Or, 1996						TDR			SD					
Corn	Darusman et al., 1997a	0.40-0.45	1.5-3.1	FD		X	T								X
Corn	Darusman et al., 1997b	0.40-0.45	1.5	FD		X	T								X
Corn	Evett et al., 1995	0.15, 0.30	1.52				NP	M		F			X		
Corn	Evett et al., 1996	0.30	1.52		X	X	NP	IRT		SD	X		X		
Corn	Howell et al., 1997	0.30	1.5	FT	X	X	NP			SD					
Corn	Kruse & Israeli, 1987	0.12-0.37	1.5												
Corn	Lamm & Manges, 1991	0.40-0.45	1.5	FD		X	NP				X		X	X	X
Corn	Lamm et al., 1995a	0.40-0.45	1.5	FD		X						X	X		X
Corn	Lamm et al., 1995b	0.45	0.76-3.05	FD	X	X					X	X			
Corn	Lamm et al., 1997a	0.40-0.45	1.5-3.0	FD		X	NP						X		
Corn	Lamm et al., 1997b	0.40-0.45	1.5	FD			NP				X		X	X	X
Corn	Manges et al., 1995	0.45	0.76-3.05												
Corn	Mitchell & Sparks, 1982	0.34-0.37	0.76							SD	X				
Corn	Mitchell, 1981	0.36	0.9	FD							X				
Corn	Oron et al., 1991	0.30	0.95, 1.90						WW	SD					
Corn	Powell & Wright, 1993	0.38	0.91, 1.82, 2.74	FD		X									
Cotton	Ayars et al., 1995	0.45	1.7	Var											
Cotton	Bar-Yosef et al., 1991	0.30, 0.45								SD	X				
Cotton	Camp et al., 1997a	0.30	1.0, 2.0	RT			T	M			X				
Cotton	DeTar et al., 1994	0.38		RT						F		X			
Cotton	Fangmeier et al., 1989	0.20	1		X	X	NP	CWSI			X		X	X	
Cotton	Henggeler, 1995	0.20-0.35	1.0-3.1							F					
Cotton	Henggeler et al., 1996														
Cotton	Hutmacher et al., 1993, 1995	0.45	1.52	RT	X	X	NP	L				X		X	
Cotton	Oron et al., 1991	0.30	0.95, 1.90						WW	SD					
Cotton	Phene et al., 1992a						NP	PE		F		X			
Cotton	Plaut et al., 1985	0.40			X	X	NP	PE		SD					X
Cotton	Tollefson, 1985a	0.25	1.0	FD							X				
Cotton	Tollefson, 1985b	0.20-0.25	1.9	FD						F	X	X			
Cotton	Zetzsche & Newman,1966	0.40	1.42	R						F					
Grain sorghum	Hiler & Howell, 1973	0.20		RI				L		SD		X	X	X	
Landscape	Gushiken, 1995	0.15-0.30	Var.						WW						X
Peanut	Adamsen, 1989	0.35-0.41	0.91	FD					SL	S		X			
Pearl millet	Payne et al., 1995	0.25	0.4	FD		X							X		
Sugarcane	Huang et al., 1982	0.30				X	G	PE		F					
Sugarcane	Moore & Fitschen, 1990	0.10	2.7	FT	X	X				F					
Trees	Shrive et al., 1994	0.15				X			WW	S, SD				X	X
Turf	Gushiken, 1995	0.15-0.30	Var.						WW						X
Turf	Solomon & Jorgensen, 1992	0.10	Var.												
Turf	Zoldoske et al., 1995	0.20	0.46	RT						S					
Wheat	Oron et al., 1991	0.30	0.95, 1.90						WW	SD					
Wheat	Senock et al., 1996	0.18-0.25	0.51									X		X	
Wheat	Tollefson, 1985b	0.20-0.25	1.9	FD						F	X	X			

* Type code definitions: FD = flexible wall, dual chamber; FT = flexible wall, turbulent flow; R = rigid; RI = rigid wall, insert orifice; RT = rigid, turbulent flow; Var. = various.
† MSW = measured soil water content. Code definition: NP = neutron probe; T = tensiometer.
‡ Other code definitions: CWSI = crop water stress index; IRT = infrared thermometer; L = lysimeter; M = crop growth model; PE = pan evaporation.
§ Water supply code definitions: SL = saline/sodic; WW = waste water.
‖ Other irrigation system code definitions: F = furrow; S = sprinkler; SD = surface drip; WT = water table.

systems are discussed later in a separate section. In all cases, crop yields for subsurface drip systems were equal to or better than other systems. In Virginia, peanut yield was greater for subsurface drip than for sprinkler irrigation when using sodic water, but there was no increase with good quality water. Corn yields were not different for the two systems with either sodic or good quality water, but subsurface drip required 30% less water (Adamsen 1989, 1992). Cotton yields were greater with subsurface drip than with furrow on a silt soil but not for a sandy soil (Phene et al., 1992a) and were equal in another study (DeTar et al., 1994); however, in both cases much less water (~40% less) was required by subsurface drip. Henggeler (1995) reported a cotton yield increase of about 20% for subsurface drip over furrow using farm data for several counties in western Texas. Alfalfa yields were similar for subsurface drip and solid set sprinklers in Hawaii, but more labor was needed to remove and set up the sprinkler system at each cutting (Bui and Osgood, 1990). Zoldoske et al. (1995) reported similar results for turfgrass on a campus with subsurface drip and sprinkler, but maintenance costs and water use were greater with the sprinkler system. Sugarcane yields were greater for subsurface drip than for furrow irrigation in Hawaii (Moore and Fitschen, 1990) and for a sandy soil in Taiwan but were equal for a sandy loam (Huang et al., 1982).

Generally, yields for surface and subsurface drip were similar for corn (Camp et al., 1989; Howell et al., 1997; Mitchell and Sparks, 1982; Powell and Wright, 1993), cotton (Bar-Yosef et al., 1991; Plaut et al., 1985), grain sorghum (Hiler and Howell, 1973), or hardwood trees irrigated with waste water (Shrive et al., 1994). In some cases, especially with cotton, the yield decline with decreasing irrigation amount was much less with subsurface drip (Plaut et al., 1985) or the yield difference was greater for subsurface drip on one soil but not another (Phene et al., 1992a).

Horticultural crop yields for subsurface drip irrigation were equal to or greater than those for other irrigation systems in most cases (table 2). Yields for subsurface drip

Table 2. Summary of information reported for subsurface drip irrigation systems on horticultural (fruit, vegetable, and tree) crops

Crop		Lateral			Scheduling/Delivery										
		Depth (m)	Spacing (m)	Type*	Tim-ing	Amt.	MSW†	Other‡	Water Supply§	Other Irrig. Syst.‖	Fert. Mgt.	Irrig. Water Req.	WUE	Plant Meas.	Environ. Effects
Apple	Barth, 1995	0.3-0.7	2-5	RS											
Asparagus	Sterrett et al., 1990	0.30		FD						SD, MS					
Banana	Gushiken, 1995	0.15-0.30	Various						WW						X
Bell pepper	Bracy et al., 1995	0.15	1			X		PE			X				
Bell pepper	Schwankel & Prichard, 1990	0.10	0.76								X				
Broccoli	Camp et al., 1993	0.30	0.76-1.52	RT	X	X	T			SD					
Cabbage	Chase, 1985b	0.08-0.13													
Cabbage	Rubeiz et al., 1989	0.15								F, SD	X	X			
Cantaloupe	Bucks et al., 1981	0.02-0.15	1.5	FS, FD	X	X				SD, F					
Cantaloupe	Phene et al., 1989	0.45		RT			NP	L		SD			X		
Carrot	Bucks et al., 1981	0.02-0.15	1.5	FS, FD	X	X				SD, F					
Carrot	Martin et al., 1996	0.18	1.0	FT		X	NP	TDR				X			
Cauliflower	Martin et al., 1996	0.18	1.0	FT		X	NP	TDR				X			
Cowpea	Camp et al., 1993	0.30	0.76-1.52	RT	X	X	T			SD					
Cucumber	El-Gindy & El-Araby, 1996	0.25	0.30		X					SD				X	
Grapes	Grimes et al., 1990	0.25, 0.30					NP			SD	X				
Grapes	Zoldoske & Norum, 1997	0.45	3.67	FT, RT			T			SD	X	X		X	
Green bean	Camp et al., 1993	0.30	0.76-1.52	RT	X	X	T			SD					
Hops	Pierzgalski, 1995	0.35-0.45	0.6-1.2	FW	X										
Lettuce	Chase, 1985a	0.07	0.30	FS							X				
Lettuce	Chase, 1985b	0.08-0.13													
Lettuce	Martin et al., 1996	0.18	1.0	FT		X	NP	TDR				X			
Lettuce	Sammis, 1980	0.10		FD			T			SD, F, S			X		
Lettuce	Scherm & van Bruggen, 1995									F				X	
Lettuce	Thompson & Doerge, 1996a	0.15	1.02	FD			T				X				
Lettuce	Thompson & Doerge, 1996b	0.15	1.02	FD			T				X			X	X
Muskmelon	Camp et al., 1993	0.30	0.76-1.52	RT	X	X	T			SD					
Okra	Batchelor et al., 1994	0.15	1.0	CP		X	NP			F			X		
Onion	Bucks et al., 1981	0.02-0.15	1.5	FS, FD	X	X				SD, F					
Onion	Martin et al., 1996	0.18	1.0	FT		X	NP	TDR				X			
Papaya	Gushiken, 1995	0.15-0.30	Various						WW						X
Pea	Oron et al., 1991	0.30	0.95, 1.90						WW	SD					
Pea	Oron et al., 1995	0.3, 0.6	5	RS					SL	SD					
Potato	Barth, 1995	0.3-0.7	2-5	RS											
Potato	DeTar et al., 1996	0.08-0.58	0.81	F			NP	PE		S					
Potato	Neibling & Brooks, 1995	0.08	0.9	FD						WL	X	X			
Potato	Phene & Sanders, 1976	0.05	1.0, 1.3	FP	X	X	T				X			X	
Potato	Phene et al., 1979	0.02	1.65	FP	X	X	MP				X			X	
Potato	Sammis, 1980	0.10		FD			T			SD, F, S			X		
Rape	Batchelor et al., 1994	0.15	1.0	CP		X	NP			F			X		
Squash	Camp et al., 1993	0.30	0.76-1.52	RT	X	X	T			SD					
Squash	Rubeiz et al., 1989	0.15								F, SD	X	X			
Sweet corn	Bar-Yosef et al., 1989	0.30		RT						SD	X				
Sweet corn	Bar-Yosef et al., 1991	0.30, 0.45								SD	X				
Sweet corn	Onken et al., 1979	0.45	1.02	RI	X	X	NP, T			F, S	X			X	X
Sweet corn	Phene & Beale, 1976	0.05	1.0	FP	X	X	MP			F, S	X			X	
Sweet corn	Phene & Beale, 1979	0.05	1.0, 1.65	FP	X	X	MP	PE			X			X	
Sweet corn	Wendt et al., 1977	0.30	1.02	RI	X		T, NP, G			S, F		X			
Tomato	Ayars et al., 1995	0.45	1.7	Var											
Tomato	Bar-Yosef et al., 1991	0.30, 0.45								SD	X				
Tomato	Batchelor et al., 1994	0.15	1.0	CP		X	NP			F			X		
Tomato	Bogle et al., 1989	0.15-0.20	2.0	FD				PE		F			X	X	
Tomato	Clark et al., 1991	0.25-0.40	1.37	FD			T			WT	X				
Tomato	Clark et al., 1993	0.30	1.5	FD						SD	X				
Tomato	Davis et al., 1985	0.45	1.63		X			L		S	X		X		
Tomato	El-Gindy & El-Araby, 1996	0.25	0.30		X					SD				X	
Tomato	Grattan et al., 1988	0.25	1.5							S, F					
Tomato	Hutmacher et al., 1985	0.45	1.63	RT	X					SD	X			X	
Tomato	Lindsay et al., 1989	0.08	1.3	FD			NP						X		
Tomato	Martin et al., 1996	0.18	1.0	FT		X	NP	TDR				X			
Tomato	Nightingale et al, 1985	0.45	1.7	FT	X					SD	X				
Tomato	Phene et al., 1987	0.45	1.63	RT	X			L		SD	X				
Tomato	Phene et al., 1989	0.45		RT			NP	L		SD			X		
Tomato	Phene et al., 1990, 1992b	0.45	1.63	RT	X					SD	X		X		
Tomato	Rose et al., 1982	0.46	1.52	RT		X	MP	PE		F					
Tomato	Schwankel et al., 1990	0.15-0.30	1.5	FT	X	X									
Tomato	Sutton et al., 1985	0.12	1.32	FD		X			SP			X	X		
Watermelon	Pier & Doerge, 1995a	0.20	2.0	FD	X		T				X				
Watermelon	Pier & Doerge, 1995b	0.20	2.0	FD	X		T				X				X

* Type definition codes: CP = clay pipe; F = furrow; FD = flexible wall, dual chamber; FP = flexible wall, porous; FS = flexible wall, single chamber; FT = flexible wall, turbulent flow FW = flexible wall, orifice in wall; RI = rigid wall, insert orifice; RS = rigid wall, micro tubing; RT = rigid, turbulent flow.
† MSW = measured soil water content. Code definition: MP = matric potential sensor; NP = neutron probe; T = tensiometer.
‡ Other definitions: L = lysimeter; PE = pan evaporation; TDR = time domain reflectometry.
§ Water supply definitions: SL = saline/sodic; SP = solar powered pump; WW = waste water.
‖ Other irrigation systems definitions: F = furrow; MS = micro sprinkler; S = sprinkler; SD = surface drip; WL = wheel line; WT = water table or seepage; Var. = various.

were 12 to 14% greater than furrow and sprinkler for sweet corn in South Carolina (Phene and Beale, 1976) and ~20% greater than for furrow with tomato in Texas (Bogle et al., 1989) and California (Rose et al., 1982), but were similar with cantaloupe, onion, and carrot in Arizona (Bucks et al., 1981) and sweet corn in Texas (Wendt et al., 1977). In Arizona, subsurface drip produced ~350% greater cabbage yields than furrow irrigation and ~35% greater zucchini yields than both furrow and surface drip irrigation (Rubeiz et al., 1989, 1991). However, adding fertilizer (urea phosphate) to furrow irrigation increased cabbage and zucchini yields to equal that of subsurface drip. Also, subsurface drip had better water utilization for zucchini because of reduced evaporation in summer. Clark et al. (1991) reported similar tomato yields for subsurface drip and seepage irrigation (subirrigation) in Florida.

Table 3. Summary of information on design, evaluation, and guidelines for subsurface drip irrigation systems

	Design/Evaluation					Guidelines/Rec.						
	Uniformity	Plugging Deformation	Longevity	Methods	Soil Wetting*	Design	Install	Operation (incl fert.)	Filtration	Root Intrusion	Other Effects†	Economics/ Profitability
Ayars et al., 1995											RL, MD	
Bar-Yosef et al., 1991		X						X				
Barth, 1995											PB	
Ben-Asher & Phene, 1993					M							
Bosch et al., 1992												X
Brown et al., 1996					WP							
Bui, 1990	X	X								X	ID, MD	
Camp et al., 1997b	X	X	X	X			X					
Chase, 1985b		X				X	X				SD, ID, MD, CT	
Coelho & Or, 1996					M							
Dhuyvetter et al., 1995												X
Dirksen, 1978					M, L							
Ghali & Svehlik, 1988					M			X			SWM	X
Gibson, 1974						X		X				
Gilley & Allred, 1974a, b					M	X					SWM	
Grattan et al., 1988											WC	
Grimes et al., 1990					X						SC	
Hanson et al., 1997					X						SWM	
Hanson & Bendixen, 1993						X		X			SS	
Henggeler et al., 1996												X
Hills et al., 1989a	X	X						X			SC	
Hills et al., 1989b	X	X				X						
Huang et al., 1982						X					MD, RD	
Isobe, 1972						X	X	X				
Jorgensen & Norum, 1993	X					X	X	X	X			
Knapp, 1993												X
Kruse & Israeli, 1987						X	X		X			
Lamm et al., 1995c						X	X	X	X			
Lanting, 1975		X				X	X					
Mikkelson, 1989								X			FM	
Mitchell, 1981	X		X								SC	
Mitchell & Sparks, 1982											SC, OM, RG	
Mitchell and Tilmon, 1982						X	X	X				
Mizyed & Kruse, 1989	X	X		X								
Nightingale et al., 1985								X			SC	
O'Brien et al., 1997												X
Phene et al., 1979								X			CM, WC	
Phene et al., 1992c	X		X	X								
Phene, 1995a	X						X				RG	
Phene & Ruskin, 1995						X	X	X			SC, WU	
Plaut et al., 1996						X					RG	
Rolston et al., 1979								X			CM	
Rubeiz et al., 1991								X			FM, SC	
Ruskin, 1992		X	X			X		X	X		WU, WQ	
Ruskin et al., 1990			X			X				X		
Sadler et al., 1995	X	X	X		X						SWM, EX	
Schwankel & Prichard., 1990											SC	
Schwankel et al., 1990											SE	
Shani et al., 1996					X	X	X				SWM	
Solomon & Jorgensen, 1992						X	X	X	X	X	EC	
Thomas et al., 1974					M						SWM	
Thomas et al., 1977					M, L	X						
Tollefson, 1985a						X						
Van Bavel et al., 1973					M							
Vaziri & Gibson, 1972						X						
Warrick et al., 1980					M	X						
Warrick & Shani, 1996	X	X				X	X	X			SWM	
Welsh et al., 1995							X				PB, SWM	
Zachmann & Thomas, 1973					M							
Zoldoske et al., 1995						X	X	X		X	EC	
Zoldoske & Norum, 1997	X	X				X	X	X			RG	

* Soil wetting definitions: L = laboratory measurements; M = model; WP = wetting pattern modification.

† Other effects code definitions: CM = chemical management; CT = conservation tillage; EC = emitter comparison/evaluation; EX = emitter excavation effect; FM = fertilizer management ID = insect damage; MD = mechanical damage; OM = organic matter; PB = plastic or foil barrier; RD = rodent damage; RG = root growth; RL = row location relative to lateral location SC = soil chemistry change, e.g. pH; SD = soil compaction; SE = seedling emergence; SS = soil salinity; SWM = soil water movement; WC = weed control; WU = use of wastewater WQ = water quality guidelines.

When compared to surface drip, subsurface drip had greater yield for sweet corn in Israel and California (Bar-Yosef et al., 1989); for potato at one site in New Mexico, but not another (Sammis, 1980); for tomato in California (Phene et al., 1987); and for asparagus transplants, but not for asparagus crowns (Sterrett et al., 1990). Yields were similar for cantaloupe, onion, and carrot in Arizona (Bucks et al., 1981); for cowpea, green bean, yellow squash, muskmelon, and broccoli in South Carolina (Camp et al., 1993); for tomato in California (Hutmacher et al., 1985); for pea and pear in Israel (Oron et al., 1991, 1995); for lettuce in New Mexico (Sammis, 1980); and for tomato and cucumber in Egypt (El-Gindy and El-Araby, 1996). Potato yield with subsurface drip was greater than for sprinkler irrigation in California (DeTar et al., 1996) and equal to or slightly greater in Idaho for wheel line irrigation (Neibling and Brooks, 1995), but subsurface drip required only 50% to 70% as much water. Clark et al. (1993) measured greater tomato yield for surface drip than for subsurface drip, but both received subirrigation for the first three weeks. Multiple vegetable and fruit crops each season have been produced using the same subsurface drip systems (Bucks et al., 1981; Camp et al., 1993).

Lateral Depth and Spacing

A general classification of lateral and emitter type was provided for each report in tables 1 and 2 if sufficient descriptive information was provided. Lateral depth was seldom a treatment variable, hence little can be said about crop yield differences with lateral depth. Lateral depths varied from 0.02 m to 0.70 m, depending upon both soil and crop. In most cases, lateral depth was probably optimized for prevailing site conditions and knowledge of the soil and its water characteristics. In those cases where several lateral depths were evaluated, little yield difference was evident. For potato, DeTar et al. (1996) found lateral depths of 0.08 m (above seed) and 0.46 m (below seed) better than intermediate or greater depths. For installations where multiple year use and tillage were a consideration, lateral depths varied from 0.20 to 0.70 m. Where tillage was not a consideration (e.g., turfgrass, alfalfa) depths were sometimes less (0.10 to 0.40 m) depending upon crop rooting depth and soil. Seed germination and seedling establishment and growth were other factors affecting lateral depth. While sprinkler or surface irrigation has often been used for germination, the need for two systems increases expense and decreases the economic return. However, the excessive amount of irrigation needed to wet the seed zone for germination with subsurface drip may result in excessive leaching and off-site environmental effects as well as increased cost. Schwankl et al. (1990) investigated three lateral depths, three tomato seed depths, and three irrigation amounts (fractions of crop evapotranspiration, E_{tc}) on a clay loam in California. They concluded that the best combination was a lateral depth of 0.15 or 0.23 m, a seed depth of 12 or 38 mm, and a daily irrigation of 0.5 E_{tc} or greater following an initial irrigation to wet the surface over each lateral. In general, the reported information suggested that laterals be placed as shallow as tillage practices allow for coarse-textured soils and at the appropriate depth to prevent or minimize surface wetting in all cases (except when needed for germination). The existence of confining soil layers that interfere with upward water movement must also be considered.

Lateral spacing also varied considerably (0.25 to 5.0 m), with narrow spacings used primarily for turfgrass and wide spacings often used for vegetable, tree, or vine crops on beds at the same spacing. For example, Devitt and Miller (1988) investigated several lateral spacings on two soils when using saline irrigation water for bermudagrass in Nevada, concluding that a 0.6-m spacing was acceptable for a sandy loam, but a closer spacing would be required for a clay. Although both soil and crop affect lateral spacing, there appears to be general agreement that alternate-row spacing (about 1.5 m) is adequate for most uniformly spaced row crops (Camp et al., 1989, 1997a; DeTar et al., 1994; Hutmacher et al., 1993; Lamm et al., 1995b; Phene and Beale, 1979; Powell and Wright, 1993). This provides a lateral for every two rows, usually located midway between the rows. For crops with alternating row spacing patterns (sugarcane and pineapple in Hawaii and some cotton), the lateral should be located about 0.8 m from each row, usually in the narrow spacing of the pattern. Some high-value crops may require closer spacings on sandy soils (Phene and Sanders, 1976) and/or in arid areas to ensure adequate salt balance and consistent crop quality and yield. Greater lateral spacings may be possible in humid areas, producing acceptable yield in years with moderate rainfall, but producing reduced yield in years with significant drought periods, especially for susceptible crops like corn. In those cases, the design decision will depend primarily upon the crop and acceptable risk level. In one study, lateral location relative to row or bed location did not affect yield, but mechanical damage to laterals was greater when located under the furrow than under the row for tomato and cotton (Ayars et al., 1995).

Water Supply

Special emphasis was placed on water supply in a few reports. Saline and deficit supplies were most common, primarily in arid areas, but two reports concerned sodic water supplies in a humid area (Adamsen, 1989, 1992). Four reports concerned the use of wastewater in subsurface drip systems. Phene and Ruskin (1995) presented a concept for use of treated wastewater on field crops and landscape plants based on experience with managing various nutrients, primarily N, and water to prevent movement out of the root zone. They provided guidelines for managing such a system, suggesting that storage would be required only in areas where cropping in winter is not possible. Ruskin (1992) also discussed problems and possible solutions for application of wastewater via subsurface drip systems. Gushiken (1995) described two large projects in Hawaii where disinfected secondary wastewater was used in permanent subsurface drip systems for a variety of landscape plants, turfgrass, and fruit and flowering trees. Domestic wastewater was used in subsurface drip systems for corn, cotton, wheat, and peas in Israel (Oron et al., 1991). Shrive et al. (1994) successfully used municipal landfill leachate to irrigate red maple and hybrid poplar trees using sprinkler, surface drip, and subsurface drip irrigation in Canada.

Irrigation Management

Irrigation Frequency. Irrigation scheduling was investigated in most reports, either in timing or amount of application, or both. Methods of scheduling irrigation applications were based on evapotranspiration (measured or calculated), pan evaporation, or direct measurements of soil and plant properties. Soil water and plant property measurement codes are indicated in tables 1 and 2 for each report. Application timing varied from multiple times each day to once each week, depending primarily on whether irrigation was intended to furnish water at the rate needed by the plant or to replace water removed from soil profile storage. Irrigation frequencies ranging from one to seven days had no effect on corn yield provided soil water storage was managed within acceptable stress levels (Caldwell et al., 1994; Camp et al., 1989; Howell et al., 1997). In a study of automated irrigation control for corn based on threshold canopy temperatures, Evett et al. (1996) concluded that the method had the potential to produce greater yield than that using full replacement of depleted soil water. For fruits and vegetables, Bucks et al. (1981) found daily better than weekly irrigation for onion and weekly better than daily for cantaloupe, and Camp et al. (1993) found no difference in multiple times per day and daily applications for several vegetable and fruit crops. El-Gindy and El-Araby (1996) reported greater tomato and cucumber yields for daily irrigation than for every three days on a calcareous soil in Egypt. Phene et al. (1990) reported that high-frequency subsurface drip irrigation applications of 1 mm, based on lysimeter measurements, produced higher tomato yields than a 25-mm application when P or P + K were injected with irrigation water.

Irrigation Amount. Irrigation amounts varied in a similar manner and were typically ratios (fractions or multiples) of a measured or calculated parameter considered optimal, such as reference ET, crop ET (E_{tc}), pan evaporation (PE), soil water depletion, or soil matric potential. Optimal amounts were determined by crop yield and/or water use efficiency (WUE). Fangmeir et al. (1989) found maximum cotton yield with 1.3 consumptive use (CU) and maximum WUE with 1.0 CU. Caldwell et al. (1994) found no effect of irrigation frequency or volume for corn in Kansas when soil water depletion was < 20%. Lamm et al. (1995a) reported statistically similar corn yields when irrigation was greater than 0.75 E_{tc}. Yield and/or plant water stress values were only slightly affected by reduced irrigation amounts (0.6-0.7 E_{tc}) for cotton (Hutmacher et al., 1995) and for corn (Howell et al., 1997) provided irrigation was adequate to maintain proper soil water depletion levels. Similarly, various fractions of pan evaporation (0.4-1.0 PE) were used to determine irrigation volume for cotton in Israel (Plaut et al., 1985) and corn in Virginia (Powell and Wright, 1993). Automatic evaporation pan systems were used to apply irrigation for cotton (Phene et al., 1992a) and potato (DeTar et al., 1996) in California, and for tree crops in an arid region (Phene, 1996).

Bucks et al. (1981) reported maximum cantaloupe and onion yields for 1.0 E_{tc}, but no difference in carrot yield for a range of irrigation amounts based on E_{tc}. For a limited water supply, Batchelor et al. (1994) investigated several irrigation amounts based on soil depletion for canola, okra, and tomato in Zimbabwe gardens and found maximum WUE values for canola at irrigation amounts as low as 0.55 to 0.85 soil water depletion. Martin et al. (1996) reported no yield differences for carrot, cauliflower, lettuce, onion, and tomato for a range of soil water depletion levels (20% to 45%) and determined crop coefficients for each crop. Davis et al. (1985) found that reduction of weekly irrigation amounts more than 14 days before harvest reduced tomato yield in California. No yield differences were found with different amounts of applied irrigation water based on pan evaporation for bell pepper in Louisiana (Bracy et al., 1995) and based on pan evaporation, E_{tc} calculations, and a soil sensor for tomato in California (Rose et al., 1982). Sutton et al. (1985) reported better tomato yield for full irrigation amount (based on soil matric potential measurement) than for two fractions of that amount in a study using two different solar-powered pumping systems. Reports where irrigation water requirements were determined are indicated in tables 1 and 2 for individual reports (crop indicated).

Many of the studies to evaluate irrigation scheduling for subsurface drip were probably initiated to determine whether reduced evaporation and improved irrigation efficiency would have a measurable effect on the irrigation requirement or its timing. The results do not answer this question conclusively—reductions in irrigation amount were found in some cases, but not in others. However, Phene et al. (1989) and Howell et al. (1997) reported E_{tc} values for subsurface drip similar to those for other irrigation systems on tomato and corn, respectively. There is probably no universal answer because several factors have influence: the amount of surface wetting by either rainfall or irrigation, degree of canopy closure during the season, and influence of rainfall and/or irrigation on root growth and activity. Realization of increased application efficiency by subsurface drip will depend upon how well irrigation application is matched to the crop water requirement.

Various types of plant measurements were included in the studies reported, varying from straightforward to sophisticated. Leaf area index, leaf water potential, and canopy temperature measurements were most common (Fangmeir et al., 1989; Hiler and Howell, 1973; Hutmacher et al., 1985, 1995; Wendt et al., 1977). Stomatal conductance was measured on tomato and cotton by Hutmacher et al. (1985, 1995) and on hardwood trees by Shrive et al. (1994). Hutmacher et al. (1995) also made several morphological and plant component measurements on cotton. Leaf wetness and incidence and severity of downey mildew on lettuce were measured by Scherm and van Bruggen (1995). Leaf photosynthesis was measured for hardwood trees by Shrive et al. (1994), and sap flow was measured for wheat by Senock et al. (1996).

Chemical Injection

One advantage of both subsurface and surface drip irrigation is the low-cost capability to apply various chemicals, including nutrients, chlorine, acids, and pesticides, at frequent intervals throughout the crop growing season. Frequent nutrient applications can also reduce leaching losses, especially N, and may reduce the fertilizer requirement. While important for any drip irrigation system, good water filtration and injection of chemicals to prevent emitter plugging is critical to long life with subsurface drip systems. The chemicals required for proper management of a system depend primarily upon the quality of the water supply, but also on soil type and conditions. Chlorine and other chemicals are required in most systems to prevent biological activity and growth within the system. Acids are often required to prevent precipitation in emitters, to periodically remove precipitates from emitters, and to control water alkalinity (pH).

Rates of specific nutrients to produce maximum crop yield or maximum economic return were discussed in several reports. No yield response to nitrogen fertilizer rate was reported by Bracy et al. (1995) for bell pepper and by Clark et al. (1991) for tomato, while reduced nitrogen rates with equal yields were reported by Camp et al. (1997a) for cotton and by Neibling and Brooks (1995) for potato. Sweet corn yield increases were reported by Phene and Beale (1979) with N and K fertilizer rates up to 168 kg/ha, but not for higher rates up to 336 kg/ha. Crop yield increases with additional phosphorus (P) fertilizer, even in soils with high available P content, were reported by Phene et al. (1986) for tomato, by Bar-Yosef et al. (1991) for sweet corn but not for cotton, and by Rubeiz et al. (1989, 1991) for cabbage and zucchini. Rubeiz and coworkers found that use of urea phosphate in calcareous soils resulted in high available P concentrations within 20 cm of the drip lateral and that two applications prolonged the P availability. Chase (1985b) reported greater lettuce yield when P was applied via the irrigation system than when applied broadcast and that more P was needed 20 weeks later for a second crop although soil P levels were high. Mikkelsen (1989) concluded that less

P is required for subsurface drip because it is placed directly in the root zone; that the distribution of P depends on soil properties, source of P, application rate, and water amount; that acidic sources of P can be effective in preventing precipitation of insoluble P salts when the irrigation water contains high concentrations of calcium and magnesium ions; and that a compatibility test of fertilizer and water should be conducted before use.

System Design and Evaluation

Design, Installation, and Management. Procedures for designing surface drip irrigation systems are generally applicable to subsurface drip systems, especially with regard to hydraulic performance and uniformity. However, good filtration, frequent system flushing, and installation of air entry ports are required to ensure long life and prevent system failure. Repair and replacement of subsurface drip systems are more expensive than surface drip systems. Many design aides and computer programs are available from state extension offices and other government agencies, and a listing of these is beyond the scope of this report. However, water distribution in the soil profile for subsurface drip is much different than for surface drip. Some mathematical models specific to subsurface drip are identified in table 3; however, this list is not intended to be comprehensive.

Philip (1968) developed mathematical theory for two- and three-dimensional unsaturated flow from buried point sources and spherical cavities. A one-dimensional, dynamic simulation model for automated subsurface drip was developed by van Bavel et al. (1973). Gilley and Allred (1974a,b) combined an analytical solution with a plant extraction model to determine lateral depth and spacing and compared predicted and measured values. Zachman and Thomas (1973) described the physics of steady infiltration from a subsurface line source, and Thomas et al. (1974) developed an analytical solution, which was compared to the original, more complex solutions of Zachman and Thomas. Thomas et al. (1977) reported similar values (few exceptions) for calculated and measured water potentials for two soils in bins with barley and corn in a greenhouse. Dirksen (1978) described transient and steady flow for four equally spaced line sources with constant head and compared predicted values with those measured in a soil box using gamma attenuation. Warrick et al. (1980) reported a mathematical model to describe three-dimensional linearized moisture flow with root extraction under steady conditions for various subsurface sources. Ben-Asher and Phene (1993) presented a numerical model to analyze two-dimensional water flow for surface and subsurface drip systems; they suggest it can be used as a first approximation in design, especially to determine optimal lateral depth and emitter spacing. Philip (1992) explored the theoretical effect of soil saturation in the immediate vicinity of a quasi-linear point source where other soil regions are unsaturated. Or (1995) used a stochastic approach to develop analytical expressions relating variations in soil hydraulic properties to expected variability in matric potential and relative saturation, which could be used to determine the number and placement of sensors. Coelho and Or (1996) presented a parametric model for two-dimensional water flow and uptake by corn for four plant-emitter configurations. Also, soil wetting patterns are provided in some of the reports that discuss models and in others shown in table 3.

Specific guidelines for design, installation, and management of subsurface drip irrigation systems are generally available from state extension offices, other government agencies, dealers, consultants, and manufacturers and are often specific to the geographic or climatic region. While not a comprehensive listing, several sources are listed in table 3. Jorgensen and Norum (1993) is probably the most comprehensive single source for systems in arid areas, but general guidelines also apply to other regions. The reader is encouraged to check local sources for guidelines more specific to an area. A few reports listed in table 3 discuss filtration requirements for subsurface drip systems. Filtration requirements are similar to those for surface systems except that the consequences of emitter plugging are greater. Plugged emitters are more difficult to locate and their replacement is more difficult and more expensive than with surface drip systems. Because emitters in subsurface drip systems are expected to operate satisfactorily for a greater duration (> 10 years), filtration techniques that reduce accumulated effects on emitter plugging may be of relatively greater importance than in surface drip systems.

Uniformity. A major concern with subsurface drip systems is evaluation of performance and uniformity. Measurement of uniformity for surface drip systems is straightforward but is much more difficult for subsurface systems because all emitters are buried and cannot be readily observed and measured. All methods used to describe application uniformity in surface drip systems can also be used in subsurface drip systems, but emitters must be excavated to measure flow rates. Measurement of system pressures and flow rates are useful in monitoring system performance and are used in several methods to determine system uniformity. Reports dealing with uniformity, emitter plugging, tube deformation, system longevity, and methods of evaluation are identified in table 3. Phene et al. (1992c) measured system uniformity for several lateral types after nine years of operation and compared measured values with those predicted by various models (Yue et al., 1993), concluding that the models could accurately predict system uniformity for subsurface drip systems, assuming that emitter plugging was minimal. Camp et al. (1997b) evaluated surface and subsurface drip systems after eight years use, reporting more reduction in uniformity for subsurface systems than for surface systems, primarily because of emitter plugging caused by soil entry into the main or sub-main during system modification. After five years use, Mitchell (1981) reported no deterioration of a porous wall lateral but observed reduced flow rates. Flow rate reduction was less for laterals where anhydrous ammonia had been injected as a nitrogen fertilizer source. Others report measured, estimated, or observed uniformity measures or emitter plugging (Bar-Yosef et al., 1991: Chase, 1985a; Lanting, 1975; Mizyed and Kruse, 1989).

Sadler et al. (1995) determined the effect of excavating subsurface emitters on emitter discharge rate and uniformity measurement and discussed errors in these determinations when soil-limiting flow causes a vertical water column between the emitter and the soil surface (back pressure). Zimmer et al. (1988) also observed upward free water movement from buried emitters on other soils. Warrick and Shani (1996) considered soil-limiting flow from subsurface emitters and suggested use of lower flow rates, more emitters, and pressure compensating emitters for improving uniformity under some soil conditions, especially for highly variable soils. Camp et al. (1997b) compared several measures of system uniformity, concluding that the methods used (except models) could be used for uniformity evaluation of subsurface drip systems. They suggested caution when evaluating systems with plugged (complete or partial) emitters because most methods assume a normal data distribution, which is not the case with emitter plugging. Because they were developed primarily for hydraulic design and uniformity of new systems, current models cannot account for the effects of emitter plugging on uniformity. Few reports directly considered root intrusion into subsurface emitters, which is a major concern with subsurface drip systems, but several offered observations or general comments. Ruskin et al. (1990) discussed the incorporation of a controlled-release herbicide into plastic emitters to prevent root entry for a period of 10 years or more when installed in the plant root zone. Solomon and Jorgensen (1992) evaluated various emitters for use in turfgrass, and all but two had root intrusion. In a final report of that study, Zoldoske et al. (1995) reported that only one emitter, one with herbicide incorporated in the plastic, had no root intrusion after five years of use.

Other Effects. Another concern often expressed with subsurface drip systems is the use of flexible laterals (thin walls) in areas where machinery traffic or natural soil consolidation might cause lateral deformation or collapse with associated reduced system flow and uniformity. Hills et al. (1989b) reported head loss, reduced flow rate, and the need to adjust lateral length as single- and double-walled tubing was deformed from circular to elliptical cross section in the laboratory. Chase (1985a) reported mechanical damage and compaction effects on laterals installed 0.08 to 0.13 m deep in beds where hand cultivation tools and mechanical traffic caused damage.

Several other reported effects related to subsurface drip systems are listed in table 3 and indicated by code in the "Other Effects" category. Two reports suggest installation of a barrier, either plastic or metal foil, below the lateral to alter water distribution and flow, primarily from vertically downward to more horizontal (Barth, 1995; Welsh et al., 1995). Brown et al. (1996) reported a small but consistent benefit of a V-shaped polyethylene strip installed beneath subsurface drip laterals, primarily causing the wetted area to be slightly higher and wider than that from a conventional installation. Others report soil chemical changes caused by various fertilizers, gypsum (Grimes et al., 1990), and organic matter (Mitchell and Sparks, 1982). Several report root growth information (Mitchell and Sparks, 1982; Phene et al., 1991; Phene, 1995a; Plaut et al., 1996), one reports insect damage to laterals (Chase, 1985a), and one recommends a lateral depth of 0.30 m to prevent rodent damage (Huang et al., 1982).

Reduced weed growth is sometimes cited as an advantage for subsurface drip irrigation because surface areas, predominantly between rows, are not irrigated. Grattan et al. (1990) reported reduced weed growth (red root pigweed and barnyardgrass) in California with subsurface drip compared to furrow and sprinkler irrigation. With half the plots treated with herbicide, subsurface drip without herbicide was at least as effective as sprinkler and furrow irrigation with herbicide. However, this result would not be expected in areas where rainfall was sufficient for weed germination and growth. Reduced soil surface wetting could also affect the microclimate and the plant environment. Scherm and van Bruggen (1995) reported a lower intensity of downey mildew in lettuce for subsurface drip than for furrow irrigation in four California locations, which was attributed to longer leaf wetness periods and a tendency toward higher daytime humidity for furrow irrigation.

Limitations

Although some limitations were mentioned in the preceding discussion, a summary of subsurface drip limitations may be helpful. Burt (1995) discussed some limitations and several grower concerns about subsurface drip irrigation, especially for permanent crops such as vines and trees. Perhaps the greatest limitation, whether real or perceived, is that most of the irrigation system is buried below the soil surface, making direct observation of water flow from individual emitters during operation impossible. Likewise, this makes evaluation of system operation and measurement of system uniformity very difficult. When system repairs are needed, more time is generally required and the cost is normally greater than for surface systems. If irrigation is needed for seed germination or plant establishment, subsurface drip may not be the preferred irrigation system, depending upon specific requirements and site conditions. Flushing manifolds are generally recommended for subsurface drip systems to facilitate system flushing, which is required to remove accumulated particles that could cause emitter plugging. Installation of air entry ports are often recommended to reduce negative pressures in laterals during system drainage, which can cause soil particles to be pulled into emitters under some conditions. System flushing, good water filtration, maintaining good water quality, and proper system management are essential for long system life. Many of these system design and management requirements and recommendations increase system cost, which may reduce the economic feasibility of subsurface drip in some cases. In some installations, shallow compacted soil layers may form because tillage was either altered or eliminated. These layers may reduce crop yield.

Economics and Environmental Aspects

Using a simulation, Bosch et al. (1992) found subsurface drip irrigation more profitable for corn and soybean in Virginia only for small areas (< 30 ha) when compared to center pivot systems (fixed and towable). In an economic analysis for corn in Kansas, Dhuyvetter et al. (1995) reported a lower return for subsurface drip than for a center pivot system, primarily because of high sensitivity to initial investment, system longevity, and corn yield. In a case study of a 195-ha farm in western Texas that converted from furrow to subsurface drip over a period of eight years because of limited water supply, Henggeler et al. (1996) reported increased profitability for cotton because of higher yield and distribution of fixed costs over a larger area. Knapp (1993) concluded that general recommendations regarding the best irrigation system are not appropriate but are dependent on many physical, biological, and economic factors, which can be handled best through development and use of computer programs and databases appropriate for the site. Another factor affecting the profitability of irrigation is the water resource and its availability and cost with time. Competition for the water resource is consistently increasing, especially in arid areas, so it is not possible to accurately predict long-term availability and cost. Hence, economic analyses are very difficult, at least for long time periods. Conversely, diminishing water supplies for agriculture require increased water conservation and application efficiency, which should increase the relative importance of subsurface drip systems.

Although several reports discuss potential reduction of off-site environmental effects of irrigation from the use of subsurface drip, none report measurements to support that intuitive conclusion. The management technique of small, frequent, irrigation applications throughout the season reduces the potential for nutrient runoff and leaching below the root zone, especially in areas where rainfall is sufficient to cause runoff and leaching. Lamm et al. (1995a) estimated deep drainage losses for conditions of their experiment in Kansas (estimated no runoff) and concluded that surface runoff and deep drainage would be minimized by using subsurface drip systems. Through use of data normalization, spatial analyses, and a partial nitrogen balance for watermelon in Arizona, Pier and Doerge (1995b) concluded that maximum yield could be obtained while maintaining calculated NO^{-3}-N in drainage water leaving the root zone to < 10 mg NO^{-3}-NL^{-1}. While limited, the evidence available generally supports the contention that subsurface drip can reduce off-site effects of irrigated agriculture.

Summary and Conclusions

A comprehensive review of published information on subsurface drip irrigation was compiled to determine the state of the art on the subject. A relatively broad definition of subsurface drip irrigation was used, one which included any lateral installed > 2 cm below the soil surface. A brief historical review of subsurface drip irrigation development indicates that it has been a part of drip irrigation development in the USA since its beginning about 1960, but interest and activity increased significantly starting in the early 1980s.

Yield responses for over 30 crops were included, either in comparisons between subsurface drip and other types of irrigation or in comparisons of lateral depth, lateral spacing, or irrigation management methods. In most cases, crop yield was greater than or equal to that for other irrigation methods, including surface drip, and required less water in many cases. Although most information was developed for arid or semi-arid conditions, where irrigation is necessary, a significant portion was developed for humid or sub-humid areas, where irrigation is supplemental.

Lateral depths ranged from 0.02 to 0.70 m, but for multiple-year use where tillage was used, the depths generally ranged from 0.20 to 0.70 m. The lateral depth should be sufficient to avoid damage from tillage or other equipment but shallow enough to wet the root zone without wetting the soil surface, except where necessary for seed germination. Lateral spacings ranged from 0.25 to 5.0 m, but most results indicated that an alternate-row spacing (normally 1.5 m) would be appropriate for most row crops. Closer spacings are usually required for turfgrass and some vegetable crops in arid areas, especially for coarse-textured soils. While these results are useful for general guidance, more specific information will be required to determine lateral depth and spacing for specific soil-crop combinations.

A considerable range of irrigation timing and irrigation amounts was reported for many crops, and most indicated a need for less irrigation water than for other types of irrigation, especially where surface wetting occurred in arid areas. The preferred timing of irrigation applications depended upon whether the strategy was to supply the total water volume as needed by the plant or to replace water extracted from the soil profile before some depletion level was reached. Evidence indicated that substantial reductions in irrigation amount could be achieved with subsurface drip when the season was started with a large water volume stored in the soil profile and all water extracted was not replaced via irrigation. On the other hand, frequent irrigations of small volume to replace E_{tc} (hourly or daily basis, 1-2 mm) were suggested for some soil-crop combinations, especially for soils with low water storage volume. Various plant and soil measurements were reported to aid in determination of irrigation timing and/or crop water requirements.

Much information was reported with regard to injection of chemicals into subsurface irrigation systems, both to apply nutrients and pesticides and to modify undesirable water and soil conditions. Nitrogen and phosphorus in various forms received the most attention, and elevated phosphorus amounts relative to that available in the soil produced positive results in some cases. General guidelines for use of phosphorus solutions in subsurface drip systems were reviewed. Frequent application of nutrients also provided positive crop results in many cases, and reduced nutrient amounts without yield reduction were reported for subsurface drip relative to other irrigation system types. Measurement of several soil properties and conditions following use of subsurface drip systems were included.

To determine lateral depth and spacing and to describe soil wetting patterns for various lateral positions relative to the plant root system, several mathematical models specific to subsurface drip were included. Some guidelines for design, installation, and management of subsurface drip systems were included for general information, but local sources should be consulted. Difficulty in monitoring performance and measurement of uniformity is often cited as a disadvantage of subsurface drip systems. Some uniformity measurements and a comparison of uniformity measures are reported, as well as a limited assessment of root intrusion into emitters and estimates of overall system longevity.

From the information reported, it appears that sufficient information exists to provide general guidance with regard to design, installation, and management of subsurface drip irrigation systems. Furthermore, a significant body of information exists to assist in determining relative advantages and disadvantages of this technology in comparison with other irrigation types. Generally, subsurface drip provides a more efficient delivery system, but the realization of this increased application efficiency will depend upon how well the application is matched to crop water and nutrient requirements. Use of subsurface drip for application of waste water, especially for turfgrass and landscape plants around homes, gardens, golf courses, and commercial areas, appears to offer great potential. Profitability and economic aspects of subsurface drip irrigation have not been determined conclusively and will depend greatly on local conditions and constraints.

REFERENCES

Adamsen, F. J. 1989. Irrigation method and water quality effect on peanut yield and grade. *Agron. J.* 81(4): 589-593.

_____. 1992. Irrigation method and water quality effects on corn yield in the Mid-Atlantic Coastal Plain. *Agron. J.* 84(5): 837-843.

ASAE Standards, 43rd Ed. 1996. S526.1. Soil and water terminology. St. Joseph, Mich.: ASAE.

Ayars, J. E., C. J. Phene, R. A. Schoneman, B. Meso, F. Dale, and J. Penland. 1995. Impact of bed location on the operation of subsurface drip irrigation systems. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 141-146. St. Joseph, Mich.: ASAE.

Barth, H. K. 1995. Resource conservation and preservation through a new subsurface irrigation system. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 168-174. St. Joseph, Mich.: ASAE.

Bar-Yosef, B., C. J. Phene, and R. B. Hutmacher. 1991. Plants response to subsurface trickle fertigation. BARD Project No. I-1116-86 Final Report. Bet Dagan, Israel: BARD.

Bar-Yosef, B., B. Sagiv, and T. Markovitch. 1989. Sweet corn response to surface and subsurface trickle phosphorus fertigation. *Agron. J.* 81(3): 443-447.

Batchelor, C. H., C. J. Lovell, M. Murata, and S. P. McGrath. 1994. Improving water use effectiveness by subsurface irrigation. *Aspects of Appl. Biol.* 38: 269-278.

Ben-Asher, J., and C. J. Phene. 1993. Analysis of surface and subsurface drip irrigation using a numerical model. In *Subsurface Drip Irrigation—Theory, Practices and Application*, 185-202. CATI Pub. No. 92 1001. Fresno, Calif.: California State University.

Bogle, C. R., T. K. Hartz, and C. Nunez. 1989. Comparison of subsurface trickle and furrow irrigation on plastic-mulched and bare soil for tomato production. *J. Am. Soc. Hort. Sci.* 114(1): 40-43.

Bosch, D. J., N. L. Powell, and F. S. Wright. 1992. An economic comparison of subsurface microirrigation with center pivot sprinkler irrigation. *J. Prod. Agric.* 5(4): 431-437.

Bracy, R. P., R. J. Edling, and E. B. Moser. 1995. Drip-irrigation management and fertilization of bell pepper in a humid area. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 181-186. St. Joseph, Mich.: ASAE.

Braud, H. J. 1970. Subsurface irrigation in the Southeast. In *Proc. Nat. Irrig. Symp.*, E1-E9. St. Joseph, Mich.: ASAE.

Brown, K. W., J. C. Thomas, S. Friedman, and A. Meiri. 1996. Wetting patterns associated with directed subsurface irrigation. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 806-811. St. Joseph, Mich.: ASAE.

Bucks, D. A. 1995. Historical developments in microirrigation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 1-5. St. Joseph, Mich.: ASAE.

Bucks, D. A., and S. Davis. 1986. Historical Development. In *Trickle Irrigation for Crop Production*, eds. F. S. Nakayama, and D. A. Bucks, 1-26. New York, N.Y.: Elsevier.

Bucks, D. A., L. J. Erie, O. F. French, F. S. Nakayama, and W. D. Pew. 1981. Subsurface trickle irrigation management with multiple cropping. *Transactions of the ASAE* 24(6): 1482-1489.

Bucks, D. A., F. S. Nakayama, and A. W. Warrick. 1982. Principles, practices, and potentialities of trickle (drip) irrigation. In *Advances in Irrigation*, ed. D. Hillel, 219-299. New York, N.Y.: Academic Press.

Bui, W. 1990. Performance of "Turbo Model" drip irrigation tubes. In *Proc. 3rd Nat. Irrig. Symp.*, 198-203. St. Joseph, Mich.: ASAE.

Bui, W., and R. V. Osgood. 1990. Subsurface irrigation trial for alfalfa in Hawaii. In *Proc. 3rd Nat. Irrig. Symp.*, 658-660. St. Joseph, Mich.: ASAE.

Burt, C. E. 1995. Is buried drip the future with permanent crops? *Irrig. Bus. Technol.* 3(1): 20-22.

Caldwell, D. S., W. E. Spurgeon, and H. L. Manges. 1994. Frequency of irrigation for subsurface drip-irrigated corn. *Transactions of the ASAE* 37(4): 1099-1103.

Camp, C. R., P. J. Bauer, and P. G. Hunt. 1997a. Subsurface drip irrigation lateral spacing and management for cotton in the southeastern Coastal Plain. *Transactions of the ASAE* 40(4): 993-999.

Camp, C. R., J. T. Garrett, E. J. Sadler, and W. J. Busscher. 1993. Microirrigation management for double-cropped vegetables in a humid area. *Transactions of the ASAE* 36(6): 1639-1644.

Camp, C. R., E. J. Sadler, and W. J. Busscher. 1989. Subsurface and alternate-middle micro irrigation for the southeastern Coastal Plain. *Transactions of the ASAE* 32(2): 451-456.

_____. 1997b. A comparison of uniformity measures for drip irrigation systems. *Transactions of the ASAE* 40(4): 1013-1020.

Cavanaugh, P. 1992. Raisin grower buries drip. *Grape Grower* 24(4): 6-8.

Chase, R. G. 1985a. Phosphorus application through a subsurface trickle system. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 1: 393-400. St. Joseph, Mich.: ASAE.

Chase, R. G. 1985b. Subsurface trickle irrigation in a continuous cropping system. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 909-914. St. Joseph, Mich.: ASAE.

Clark, G. A., C. D. Stanley, and D. N. Maynard. 1993. Surface vs. subsurface drip irrigation of tomatoes on a sandy soil. *Proc. Fla. State Hort. Soc.* 106: 210-212.

Clark, G. A., C. D. Stanley, D. N. Maynard, G. J. Hochmuth, E. A. Hanlon, and D. Z. Haman. 1991. Water and fertilizer management of microirrigated fresh market tomatoes. *Transactions of the ASAE* 34(2): 429-435.

Coelho, F. E., and D. Or. 1996. A parametric model for two-dimensional water uptake intensity by corn roots under drip irrigation. *Soil Sci. Soc. Am. J.* 60(4): 1039-1049.

Darusman, A. H. Khan, L. R. Stone, and F. R. Lamm. 1997a. Water flux below the root zone vs. dripline spacing in drip-irrigated corn. *Soil Sci. Soc. Am. J.* 61(6): 1755- 1760.

Darusman, A. H. Khan, L. R. Stone, and F. R. Lamm. 1997b. Water flux below the root zone vs. irrigation amount in drip-irrigated corn. *Agron. J.* 89(3): 375-379.

Davis, K. R., C. J. Phene, R. L. McCormick, R. B. Hutmacher, and D. W. Meek. 1985. Trickle frequency and installation depth effects on tomatoes. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 896-902. St. Joseph, Mich.: ASAE.

Davis, S. 1967. Subsurface irrigation—How soon a reality? *Agricultural Engineering* 48(11): 654-655.

Davis, S., and S. D. Nelson. 1970a. Subsurface irrigation today and tomorrow in California. In *Proc. Nat. Irrigation Symp.*, H1-H8. St. Joseph, Mich.: ASAE.

Davis, S., and S. D. Nelson. 1970b. Subsurface irrigation easily automated. *J. Irrig. Drain. Div., ASCE* 96(IR1): 47-51.

Davis, S., and W. J. Pugh. 1974. Drip irrigation: Surface and subsurface compared with sprinkler and furrow. In *Proc. 2nd Int'l. Drip Irrigation Congress*, 109-114. Riverside, Calif.: University of California.

DeTar, W. R., G. T. Browne, C. J. Phene, and B. L. Sanden. 1996. Real-time irrigation scheduling of potatoes with sprinkler and subsurface drip systems. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 812-824. St. Joseph, Mich.: ASAE.

DeTar, W. R., C. J. Phene, and D. A. Clark. 1994. Subsurface drip vs furrow irrigation: 4 years of continuous cotton on sandy soil. In *Beltwide Cotton Conf.*, 542-545. Memphis, Tenn.: Nat. Cotton Council.

Devitt, D. A., and W. W. Miller. 1988. Subsurface drip irrigation of bermudagrass with saline water. *Applied Agric. Res.* 3(3): 133-143.

Dhuyvetter, K. C., F. R. Lamm, and D. H. Rogers. 1995. Subsurface drip irrigation (SDI) for field corn—An economic analysis. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 395-401. St. Joseph, Mich.: ASAE.

Dirksen, C. 1978. Transient and steady flow from subsurface line sources at constant hydraulic head in anisotropic soil. *Transactions of the ASAE* 21(5): 913-919.

Duncan, J. 1993. Buried drip gains more ground. *Grape Grower* 25(4): 20-23.

Edwards, D. M., J. D. Eastin, R. A. Olson, and R. German. 1970. Subsurface irrigation today and tomorrow in the Midwest. In *Proc. Nat. Irrigation Symp.*, G1-G11. St. Joseph, Mich.: ASAE.

El-Gindy, A. M., and A. M. El-Araby. 1996. Vegetable crop response to surface and subsurface drip under calcareous soil. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 1021-1028. St. Joseph, Mich.: ASAE

Evett, S. R., T. A. Howell, and A. D. Schneider. 1995. Energy and water balances for surface and subsurface drip irrigated corn. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 135-140. St. Joseph, Mich.: ASAE.

Evett, S. R., T. A. Howell, A. D. Schneider, D. R. Upchurch, and D. F. Wanjura. 1996. Canopy temperature based automatic irrigation control. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 207-213. St. Joseph, Mich.: ASAE.

Fangmeier, D. D., D. J. Garrot Jr., S. H. Husman, and J. Perez. 1989. Cotton water stress under trickle irrigation. *Transactions of the ASAE* 32(6): 1955-1959.

Ghali, G. S., and Z. J. Svehlik. 1988. Soil-water dynamics and optimum operating regime in trickle-irrigated fields. *Agric. Water Manage.* 13: 127-143.

Gibson, W. 1974. Hydraulics, mechanics and economics of subsurface and drip irrigation of Hawaiian sugarcane, 2: 639-648. In *Proc. 15th Congress Int'l. Society Sugar Cane Technol.* Honolulu, Hawaii: Hawaiian Sugar Planters' Assoc.

Gilley, J. R., and E. R. Allred. 1974a. Infiltration and root extraction from subsurface irrigation laterals. *Transactions of the ASAE* 17(5): 927-933.

______. 1974b. Optimum lateral placement for subsurface irrigation systems. In *Proc. 2nd Int'l. Drip Irrigation Congress*, 234-239. Riverside, Calif.: Univ. Calif.

Goldberg, D., B. Gornat, and D. Rimon. 1976. *Drip Irrigation—Principles, Design and Agricultural Practices.* Kfar Shmaryahu, Israel: Drip Irrigation Scientific Publications.

Goldberg, D., and M. Shmueli. 1970. Drip irrigation—A method used under arid and desert conditions of high water and soil salinity. *Transactions of the ASAE* 13(1): 38-41.

Grattan, S. R., L. J. Schwankl, and W. T. Lanini. 1988. Weed control by subsurface drip irrigation. *California Agric.* 42(3): 22-24.

Grattan, S. R., L. J. Schwankl, and W. T. Lanini. 1990. Distribution of annual weeds in relation to irrigation method. In *Proc. 3rd Nat. Irrig. Symp.*, 148-153. St. Joseph, Mich.: ASAE.

Grimes, D. W., D. S. Munk, and D. A. Goldhamer. 1990. Drip irrigation emitter depth placement in a slowly permeable soil. In *Proc. 3rd Nat. Irrig. Symp.*, 248-254. St. Joseph, Mich.: ASAE.

Gushiken, E. C. 1995. Irrigating with reclaimed water through permanent subsurface drip irrigation systems. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 269-274. St. Joseph, Mich.: ASAE.

Hall, B. J. 1985. History of drip/trickle irrigation. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 1-7. St. Joseph, Mich.: ASAE.

Hanson, B. R., and W. E. Bendixen. 1993. Salinity under drip irrigation of row crops. In *Proc. Int'l. Exposition and Technical Conf.*, 196-202. Arlington, Va.: Irrig. Assoc.

Hanson, B. R., D. M. May, and W. E. Bendixen. 1997. Wetting patterns under surface and subsurface drip irrigation. ASAE Paper No. 97-2178. St. Joseph, Mich.: ASAE.

Hanson, E. G., and T. C. Patterson. 1974. Vegetable production and water-use efficiency as influenced by drip, sprinkler, subsurface, and furrow irrigation methods. In *Proc. 2nd Int'l. Drip Irrigation Congress*, 97-102. Riverside, Calif.: University of California.

Hanson, E. G., B. C. Williams, D. D. Fangmeier, and O. C. Wilke. 1970. Influence of subsurface irrigation on crop yields and water use. In *Proc. Nat. Irrig. Symp.*, D1-D13. St. Joseph, Mich.: ASAE.

Henggeler, J. C. 1995. A history of drip-irrigated cotton in Texas. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 669-674. St. Joseph, Mich.: ASAE.

Henggeler, J., J. Kinnibrugh, W. Multer, D. Kight, and R. Scott. 1996. Economic impact resulting from the adoption of drip irrigation cotton. Result Demonstration Report. College Station, Tex.: Texas Agric. Ext. Serv., Texas A&M University.

Hiler, E. A., and T. A. Howell. 1973. Grain sorghum response to trickle and subsurface irrigation. *Transactions of the ASAE* 16(4): 799-803.

Hills, D. J., F. M. Nawar, and P. M. Waller. 1989a. Effects of chemical clogging on drip-tape uniformity. *Transactions of the ASAE* 32(4): 1202-1206.

Hills, D. J., M. A. M. Tajrishy, and Y. Gu. 1989b. Hydraulic considerations for compressed subsurface drip-tape. *Transactions of the ASAE* 32(4): 1197-1201.

Howell, T. A., D. A. Bucks, and J. L. Chesness. 1980. Advances in trickle irrigation. In *Proc. 2nd Nat. Irrigation Symp.*, 69-94. St. Joseph, Mich.: ASAE.

Howell, T. A., A. D. Schneider, and S. R. Evett. 1997. Subsurface and surface microirrigation of corn—Southern High Plains. *Transactions of the ASAE* 40(3): 635-641.

Huang, T.-J., Y.-H. Chang, P.-C. Yang, and Y.-T. Fang. 1982. Studies on subsurface drip irrigation for coarse-texture sugarcane field in Taiwan. In *Report of the Taiwan Sugar Research Institute*, 13-32. Tainan, Taiwan: Taiwan Sugar Res. Inst.

Hutmacher, R. B., C. J. Phene, K. R. Davis, and T. A. Kerby. 1993. Acala and pima cotton responses to subsurface drip irrigation: Water use, plant water relations, and yield. In *Proc. Beltwide Cotton Conf.*, 1221-1224. Memphis, Tenn: Nat. Cotton Council.

Hutmacher, R. B., C. J. Phene, K. R. Davis, S. S. Vail, T. A. Kerby, M. Peters, C. A. Hawk, M. Keeley, D. A. Clark, D. Ballard, and N. Hudson. 1995. Evapotranspiration, fertility management for subsurface drip acala and pima cotton. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 147-154. St. Joseph, Mich.: ASAE.

Hutmacher, R. B., S. S. Vail, J. G. Muthamia, V. Mwaja, and R.C. Liu. 1985. Effect of trickle irrigation frequency and installation depth on tomato growth and water status. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 798-804. St. Joseph, Mich.: ASAE.

Isobe, M. 1972. Agronomic research in subsurface and drip irrigation. In *31st Report Hawaii Sugar Technol. Ann. Conf.*, 23-26. Honolulu, Hawaii: Hawaiian Sugar Planters' Assoc.

Jorgensen, G. S., and K. N. Norum, ed. 1993. *Subsurface Drip Irrigation—Theory, Practices and Application.* CATI Pub. No. 92 1001. Fresno, Calif.: California State University.

Knapp, K. C. 1993. Economics of irrigation system investment. In *Subsurface Drip Irrigation—Theory, Practices and Application*, 127-139. CATI Pub. No. 92 1001. Fresno, Calif.: California State University.

Kruse, E. G., and I. Israeli. 1987. Evaluation of a subsurface drip irrigation system. ASAE Paper No. 87-2034. St. Joseph, Mich.: ASAE.

Lamm, F. R., G. A. Clark, M. Yitayew, R. A. Schoneman, R. M. Mead, and A. D. Schneider. 1995c. Installation issues for SDI systems. In *Proc. Int'l. Exposition and Technical Conf.*, 29-35. Arlington, Va.: Irrig. Assoc.

Lamm, F. R., and H. L. Manges. 1991. Nitrogen fertilizer for drip-irrigated corn in northwest Kansas. ASAE Paper No. 91-2596. St. Joseph, Mich.: ASAE.

Lamm, F. R., H. L. Manges, L. R. Stone, A. H. Khan, and D. H. Rogers. 1995a. Water requirement of subsurface drip-irrigated corn in northwest Kansas. *Transactions of the ASAE* 38(2): 441-448.

Lamm, F. R., A. J. Schlegel, and G. A. Clark. 1997b. Nitrogen fertigation for corn using SDI: A BMP. ASAE Paper No. 97-2174. St. Joseph, Mich.: ASAE.

Lamm, F. R., W. E. Spurgeon, D. H. Rogers, and H. L. Manges. 1995b. Corn production using subsurface drip irrigation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 388-394. St. Joseph, Mich.: ASAE.

Lamm, F. R., L. R. Stone, H. L. Manges, and D. M. O'Brien. 1997a. Optimum lateral spacing for subsurface drip-irrigated corn. *Transactions of the ASAE* 40(4): 1021-1027.

Lanting, S. 1975. Subsurface irrigation—Engineering research. In *34th Report Hawaii Sugar Technol. Annual Conf.*, 57-62. Honolulu, Hawaii: Hawaiian Sugar Planters' Assoc.

Lee, C. O. 1920. Irrigation tile. U.S. Patent No. 1,350,229.

Lindsay, C. A., B. G. Sutton, and N. Collis-George. 1989. Irrigation scheduling of subsurface drip-irrigated salad tomatoes. *Acta Hort.* 247: 229-232.

Manges, H. L., W. E. Spurgeon, Z. M. Huang, and D. J. Tomsicek. 1995. Subsurface dripline spacing and plant population for corn production. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 382-387. St. Joseph, Mich.: ASAE.

Martin, E. C., D. C. Slack, and E. J. Pegelow. 1996. Crop coefficients for vegetables in Central Arizona. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 381-386. St. Joseph, Mich.: ASAE

McNamara, J. B. 1970. Subirrigation—The basis of tomorrow's agriculture. In *Proc. Nat. Irrigation Symp.*, C1-C13. St. Joseph, Mich.: ASAE.

Mead, R. M., R. B. Hutmacher, and C. J. Phene. 1993. Subsurface drip irrigation of alfalfa. In *Subsurface Drip Irrigation—Theory, Practices and Application*, 145-146. CATI Pub. No. 92 1001. Fresno, Calif.: California State University.

Mikkelsen, R. L. 1989. Phosphorus fertilization through drip irrigation. *J. Prod. Agric.* 2(3): 279-286.

Mitchell, W. H. 1981. Subsurface irrigation and fertilization of field corn. *Agron. J.* 73(6): 913-916.

Mitchell, W. H., and D. L. Sparks. 1982. Influence of subsurface irrigation and organic additions on top and root growth of field corn. *Agron. J.* 74(6): 1084-1088.

Mitchell, W. H., and H. D. Tilmon. 1982. Underground trickle irrigation: The best system for small farms? *Crops Soils* 34: 9-13.

Mizyed, N., and E. G. Kruse. 1989. Emitter discharge evaluation of subsurface trickle irrigation systems. *Transactions of the ASAE* 32(4): 1223-1228.

Moore, R. C., and J. C. Fitschen. 1990. The drip irrigation revolution in the Hawaiian sugarcane industry. In *Proc. 3rd Nat. Irrigation Symp.*, 223-227. St. Joseph, Mich.: ASAE.

Neibling, H., and R. Brooks. 1995. Potato production using subsurface drip irrigation—Water and nitrogen management. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 656-663. St. Joseph, Mich.: ASAE.

Nightingale, H. I., C. J. Phene, and S. H. Patton. 1985. Trickle irrigation effects on soil chemical properties. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 730-735. St. Joseph, Mich.: ASAE.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1997. Economics of SDI for corn in western Kansas. ASAE Paper No. 97-2072. St. Joseph, Mich.: ASAE.

Onken, A. B., C. W. Wendt, O. C. Wilke, R. S. Hargrove, W. Bausch, and L. Barnes. 1979. Irrigation system effects on applied fertilizer nitrogen movement in soil. *Soil Sci. Soc. Am. J.* 43(2): 367-372.

Or, D. 1995. Soil water sensor placement and interpretation for drip irrigation management in heterogeneous soil. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 214-221. St. Joseph, Mich.: ASAE.

Oron, G., Y. DeMalach, L. Gillerman, and I. David. 1995. Pear response to saline water application under subsurface drip irrigation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 97-103. St. Joseph, Mich.: ASAE.

Oron, G., J. DeMalach, Z. Hoffman, and R. Cibotaru. 1991. Subsurface microirrigation with effluent. *J. Irrig. Drain. Engng.* 117(1): 25-36.

Payne, W. A., B. Gerard, and M. C. Klaij. 1995. Subsurface drip irrigation to evaluate transpiration ratios of pearl millet. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 923-931. St. Joseph, Mich.: ASAE.

Phene, C. J. 1974. High-frequency porous tube irrigation for water-nitrogen management in humid regions. In *Proc. 2nd Int'l. Drip Irrigation Congress*, 166-171. Riverside, Calif.: University of California.

______. 1995a. The sustainability and potential of subsurface drip irrigation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 359-367. St. Joseph, Mich.: ASAE.

______. 1995b. Research trends in microirrigation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 6-24. St. Joseph, Mich.: ASAE.

Phene, C. J., and O. W. Beale. 1976. High-frequency irrigation for water nutrient management in humid regions. *Soil Sci. Soc. Am. J.* 40(3): 430-436.

______. 1979. Influence of twin-row spacing and nitrogen rates on high-frequency trickle-irrigated sweet corn. *Soil Sci. Soc. Am. J.* 43(6): 1216-1221.

Phene, C. J., and R. Ruskin. 1995. Potential of subsurface drip irrigation for management of nitrate in wastewater. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 155-167. St. Joseph, Mich.: ASAE.

Phene, C. J., and D. C. Sanders. 1976. High-frequency trickle irrigation and row spacing effects on yield and quality of potatoes. *Agron. J.* 68(4): 602-607.

Phene, C. J., B. Bar-Yosef, R. B. Hutmacher, S. H. Patton, K. R. Davis, and R. L. McCormick. 1986. Fertilization of high-yielding subsurface trickle irrigated tomatoes. In *Proc. 34th Ann. Calif. Fertilizer Conf.*, 33-43, Fresno, Calif. Sponsored by the Soil Improvement Committee of California Fertilizer Assoc.

Phene, C. J., K. R. Davis, R. B. Hutmacher, and R. L. McCormick. 1987. Advantages of subsurface irrigation for processing tomatoes. *Acta Hort.* 200: 101-114.

Phene, C. J., K. R. Davis, R. B. Hutmacher, B. Bar-Yosef, D. W. Meek, and J. Misaki. 1991. Effect of high frequency surface and subsurface drip irrigation on root distribution of sweet corn. *Irr. Sci.* 12(2): 135-140.

Phene, C. J., W. R. DeTar, and D. A. Clark. 1992a. Real-time irrigation scheduling of cotton with an automated pan evaporation system. *Applied Engineering in Agriculture* 8(6): 787-793.

Phene, C. J., J. L. Fouss, and D. C. Sanders. 1979. Water-nutrient-herbicide management of potatoes with trickle irrigation. *Am. Potato J.* 56: 51-59.

Phene, C. J., R. B. Hutmacher, and K. R. Davis. 1992b. Two hundred tons per hectare of processing tomatoes—Can we reach it? *HortTechnol.* 2(1): 16-22.

Phene, C. J., R. B. Hutmacher, K. R. Davis, and R. L. McCormick. 1990. Water- fertilizer management of processing tomatoes. *Acta Hort.* 277: 137-143.

Phene, C. J., R. L. McCormick, K. R. Davis, J. D. Pierro, and D. W. Meek. 1989. A lysimeter feedback irrigation controller system for evapotranspiration measurements and real time irrigation scheduling. *Transactions of the ASAE* 32(2): 477-484.

Phene, C. J., R. Yue, I. P. Wu, J. E. Ayars, R. A. Schoneman, and B. Meso. 1992c. Distribution uniformity of subsurface drip irrigation systems. ASAE Paper No. 92-2569. St. Joseph, Mich.: ASAE.

Phene, R. C. 1996. Real-time irrigation scheduling with automated evaporation pan systems. In *Proc. Int'l. Conf. on Evapotranspiration and Irrigation Scheduling*, eds. C. R. Camp, E. J. Sadler, and R. E. Yoder, 1093-1098. St. Joseph, Mich.: ASAE.

Philip, J. R. 1968. Steady infiltration from buried point sources and spherical cavities. *Water Resour. Res.* 4(5): 1039-1047.

______. 1992. What happens near a quasi-linear point source? *Water Resour. Res.* 28(1): 47-52.

Pier, J. W., and T. A. Doerge. 1995a. Nitrogen and water interactions in trickle-irrigated watermelon. *Soil Sci. Soc. Am. J.* 59(1): 145-150.

______. 1995b. Concurrent evaluation of agronomic, economic, and environmental aspects of trickle-irrigated watermelon production. *J. Environ. Qual.* 24(1): 79-86.

Pierzgalski, E. 1995. Application of subsurface irrigation on a hop plantation. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 729-734. St. Joseph, Mich.: ASAE.

Plaut, Z., A. Carmi, and A. Grava. 1996. Cotton root and shoot responses to subsurface drip irrigation and partial wetting of the upper soil profile. *Irrig. Sci.* 16(3): 107-113.

Plaut, Z., M. Rom, and A. Meiri. 1985. Cotton response to subsurface trickle irrigation. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 916-920. St. Joseph, Mich.: ASAE.

Powell, N. L., and F. S. Wright. 1993. Grain yield of subsurface microirrigated corn as affected by irrigation line spacing. *Agron. J.* 85(6): 1164-1169.

Rolston, D. E., R. S. Rauschkolb, C. J. Phene, R. J. Miller, K. Uriu, R. M. Carlson, and D. W. Henderson. 1979. Applying nutrients and other chemicals to trickle-irrigated crops. Univ. of Calif. Bulletin No. 1893. Davis, Calif.: Univ. Calif.

Rose, J. L., R. L. Chavez, C. J. Phene, and M. M. S. Hile. 1982. Subsurface drip irrigation of processing tomatoes. In *Proc. Specialty Conf. on Environmentally Sound Water and Soil Management*, eds. E. G. Kruse, C. R. Burdick, and Y. A. Yousef, 369-376. New York, N.Y.: ASCE.

Rubeiz, I. G., N. F. Oebker, and J. L. Stroehlein. 1989. Subsurface drip irrigation and urea phosphate fertigation for vegetables on calcareous soils. *J. Plant Nutrition* 12(12): 1457-1465.

Rubeiz, I. G., J. L. Stroehlein, and N. F. Oebker. 1991. Effect of irrigation methods on urea phosphate reactions in calcareous soils. *Commun. Soil Sci. Plant Anal.* 22(5&6): 431-435.

Ruskin, R. 1992. Reclaimed water and subsurface irrigation. ASAE Paper No. 92-2578. St. Joseph, Mich.: ASAE.

Ruskin, R., P. Van Voris, and D. A. Cataldo. 1990. Root intrusion protection of buried drip irrigation devices with slow-release herbicides. In *Proc. 3rd Nat. Irrigation Symp.*, 211-216. St. Joseph, Mich.: ASAE.

Sadler, E. J., C. R. Camp, and W. J. Busscher. 1995. Emitter flow rate changes caused by excavating subsurface microirrigation tubing. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 763-768. St. Joseph, Mich.: ASAE.

Sammis, T. W. 1980. Comparison of sprinkler, trickle, subsurface, and furrow irrigation methods for row crops. *Agron. J.* 72(5): 701-704.

Scherm, H., and A. H. C. van Bruggen. 1995. Comparative study of microclimate and downy mildew development in subsurface drip- and furrow-irrigated lettuce fields in California. *Plant Disease* 79(6): 620-625.

Schwankel, L. J., S. R. Grattan, and E. M. Miyao. 1990. Drip irrigation burial depth and seed planting depth effects on tomato germination. In *Proc. 3rd Nat. Irrigation Symp.*, 682-687. St. Joseph, Mich.: ASAE.

Schwankel, L. J., and T. L. Prichard. 1990. Clogging of buried drip irrigation systems. *California Agric.* 44(1): 16-17.

Senock, R. S., J. M. Ham, T. M. Loughin, B. A. Kimball, D. J. Hunsaker, P. J. Pinter, G. W. Wall, R. L. Garcia, and R. L. LaMorte. 1996. Sap flow in wheat under free-air CO_2 enrichment. *Plant, Cell & Environ.* 19(2): 147-158.

Shani, U., S. Xue, R. Gordin-Katz, and A. W. Warrick. 1996. Soil-limiting flow from subsurface emitters. I. Pressure measurements. *J. Irrig. Drain. Engng.* 122(5): 291-295.

Shrive, S. C., R. A. McBride, and A. M. Gordon. 1994. Photosynthetic and growth responses of two broad-leaf tree species to irrigation with municipal landfill leachate. *J. Environ. Qual.* 23(3): 534-542.

Solomon, K. H., and G. Jorgensen. 1992. Subsurface drip irrigation. *Grounds Maintenance* 27(10): 24, 26.

Sterrett, S. B., B. B. Ross, and C. P. Savage Jr. 1990. Establishment and yield of asparagus as influenced by planting and irrigation method. *J. Am. Soc. Hort. Sci.* 115(1): 29-33.

Sutton, B. G., R. J. Stirzaker, C. J. Doney, and S. D. English. 1985. Solar powered drip irrigation for vegetables. In *Proc. 3rd Int'l. Drip/Trickle Irrig. Congress*, 2: 589-593. St. Joseph, Mich.: ASAE.

Thomas, A. W., H. R. Duke, and E. G. Kruse. 1977. Capillary potential distributions in root zones using subsurface irrigation. *Transactions of the ASAE* 20(1): 62-67, 75.

Thomas, A. W., E. G. Kruse, and H. R. Duke. 1974. Steady infiltration from line sources buried in soil. *Transactions of the ASAE* 17(1): 125-133.

Thompson, T. L., and T. A. Doerge. 1996a. Nitrogen and water interactions in subsurface trickle-irrigated leaf lettuce. I. Plant response. *Soil Sci. Soc. Am. J.* 60(1): 163-168.

______. 1996b. Nitrogen and water interactions in subsurface trickle-irrigated leaf lettuce. II. Agronomic, economic, and environmental outcomes. *Soil Sci. Soc. Am. J.* 60(1): 168-173.

Tollefson, S. 1985a. The Arizona system: Drip irrigation design for cotton. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 1: 401-405. St. Joseph, Mich.: ASAE.

______. 1985b. Subsurface drip irrigation of cotton and small grains. In *Proc. 3rd Int'l. Drip/Trickle Irrigation Congress*, 2: 887-895. St. Joseph, Mich.: ASAE.

van Bavel, C. H. M., J. Ahmed, S. I. Bhuiyan, E. A. Hiler, and A. G. Smajstrla. 1973. Dynamic simulation of automated subsurface irrigation systems. *Transactions of the ASAE* 16(6): 1095-1099.

Vaziri, C. M., and W. Gibson. 1972. Subsurface and drip irrigation for Hawaiian sugarcane. In *31st Report Hawaii Sugar Technol. Annual Conf.*, 18-22. Honolulu, Hawaii: Hawaiian Sugar Planters' Assoc.

Warrick, A. W., D. O. Lomen, and A. Amoozegar-Fard. 1980. Linearized moisture flow with root extraction for three dimensional, steady conditions. *Soil Sci. Soc. Am. J.* 44(5): 911-914.

Warrick, A. W., and U. Shani. 1996. Soil-limiting flow from subsurface emitters. II. Effect on uniformity. *J. Irrig. Drain. Engng.* 122(5): 296-300.

Welsh, D. F., U. P. Kreuter, and J. D. Byles. 1995. Enhancing subsurface drip irrigation through vector flow. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 688-693. St. Joseph, Mich.: ASAE.

Wendt, C. W., A. B. Onken, O. C. Wilke, R. Hargrove, W. Bausch, and L. Barnes. 1977. Effect of irrigation systems on the water requirement of sweet corn. *Soil Sci. Soc. Am. J.* 41(4): 785-788.

Whitney, L. F. 1970. Review of subsurface irrigation in the Northeast. In *Proc. Nat. Irrig. Symp.*, F1-F8. St. Joseph, Mich.: ASAE.

Whitney, L. F., and K. M. Lo. 1969. Plastic orifice inserts for subsurface irrigation. *Transactions of the ASAE* 12(5): 602-607.

Yue, R., C. J. Phene, F. Dale, J. E. Ayars, R. A. Schoneman, I.-P. Wu, and L. Kong. 1993. Field uniformity of subsurface drip irrigation. In *Subsurface Drip Irrigation—Theory, Practices and Application*, 181-183. CATI Pub. No. 92 1001. Fresno, Calif.: California State University.

Zachmann, D. W., and A. W. Thomas. 1973. A mathematical investigation of steady infiltration from line sources. *Soil Sci. Soc. Am. Proc.* 37(4): 495-500.

Zetzsche, J. B., and J. S. Newman. 1966. Subirrigation with plastic pipe. *Agricultural Engineering* 47(1): 74-75.

Zimmer, A. L., M. J. McFarland, and J. Moore. 1988. Upward free water movement from buried trickle emitters. ASAE Paper No. 88-2063. St. Joseph, Mich.: ASAE.

Zoldoske, D. F. 1993. The future of irrigation is buried. In *Proc. Int'l. Irrigation Expo and Technical Conf.*, 86-88. Arlington, Va.: Irrig. Assoc.

Zoldoske, D. F., S. Genito, and G. S. Jorgensen. 1995. Subsurface drip irrigation (SDI) on turfgrass: A university experience. In *Proc. 5th Int'l. Microirrigation Congress*, ed. F. R. Lamm, 300-302. St. Joseph, Mich.: ASAE.

Zoldoske, D. F., and E. M. Norum. 1997. Final Report. Progress report on the Lehman Farms Project: A case study in the conversion of an old vineyard from flood to surface drip (SDI) and subsurface drip (SSDI) irrigation. Center for Irrig. Tech., Pub. No. 970702. Fresno, Calif.: California State University.