DRIP IRRIGATION AS A SUSTAINABLE PRACTICE UNDER SALINE SHALLOW GROUND WATER CONDITIONS

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ABSTRACT

Subsurface drainage systems cannot be used for addressing the saline, shallow ground water conditions of the San Joaquin Valley, California because no drainage water disposal facilities exist in the valley. Thus, the salinity/drainage problem of the valley must be addressed through improved irrigation practices such as converting to drip irrigation. Experiments in four commercial fields evaluated the effect of subsurface drip irrigation on processing tomato yield and quality, soil salinity, soil water content, and water table depth. The HYDRUS-2D computer simulation model evaluated leaching with subsurface drip irrigation under saline, shallow ground water conditions. Drip irrigation of processing tomatoes was highly profitable under these conditions compared to sprinkle irrigation. No trend in tomato yield was found with soil salinity levels. A water balance showed little or no field-wide leaching in the commercial fields, yet soil salinity data and computer modeling clearly showed localized leaching around the drip lines.

INTRODUCTION AND BACKGROUND

About 400,000 ha of salt affected irrigated land exist along the west side of the San Joaquin Valley, California. Upward flow of the saline, shallow groundwater is the main source of the salts. Subsurface drainage systems, traditionally used for coping with shallow ground water problems, cannot be used because no economically, technically, and environmentally feasible drain water disposal method exists for the valley. Thus, options such as better management of irrigation water to reduce drainage below the root zone, increasing crop water use of the shallow groundwater without any yield reductions, and drainage water reuse for irrigation must be implemented to deal with the shallow ground water conditions (Hanson and Ayars, 2002). Shoups et al., (2005) concluded that for irrigated agriculture to remain sustainable, a soil salt balance must be maintained that allows for productive cropping systems and continued irrigation without changing management practices is not sustainable.

Converting from furrow or sprinkler irrigation to drip irrigation is one option for growers in the salt affected areas. Drip irrigation can apply water both precisely and uniformly compared with

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furrow and sprinkler irrigation thus potentially increasing yield, reducing root zone soil salinity, and reducing subsurface drainage. This potential is not only governed by the technology, but also design, installation, operation, and maintenance of drip irrigation systems. The main disadvantage of drip irrigation is its cost, which can be as much as \$2,470 ha^{-1}.

For drip irrigation to be sustainable, it must be profitable. Yet, several large-scale comparisons of furrow and drip irrigation of cotton revealed mixed economic benefits of drip irrigation. At one location, furrow irrigation was clearly more profitable than drip irrigation (Fulton et al., 1991), while at a second location, drip irrigation was slightly more profitable (Styles et al., 1997). Thus, growers converting to drip irrigation of cotton face uncertainty about the economic risks involved.

Subsurface drip irrigation of high-cash value processing tomatoes has a potential for high profits compared to cotton. However, tomatoes are more salt sensitive than cotton, creating a potential for reduced tomato yields in salt affected soil. The effect of subsurface drip irrigation of processing tomatoes was evaluated under saline, shallow ground water conditions to determine its effect on crop yield and quality, soil salinity, leaching fraction, water table depth, and profitability.

METHODS AND MATERIALS

Field experiments were conducted in four commercial fields to determine the effect of subsurface drip irrigation. In addition, the computer simulation model HYDRUS-2D was used to evaluate leaching with subsurface drip irrigation under saline, shallow ground water conditions.

Field Experiments

Experiments in three commercial fields compared subsurface drip irrigation of processing tomatoes with sprinkle irrigation under saline, shallow ground water conditions. The drip irrigation systems ranged from 16 ha to 32 ha in size with drip lines buried 0.2 to 0.30 m deep and drip line lengths of 400 m. Drip irrigations occurred every two to three days. Water table depths ranged from 0.5 m to 2 m, depending of the field location. The electrical conductivity (EC) of the irrigation water ranged from 0.30 to 0.35 dS m^{-1} (irrigation district water) to 1.06 to 1.2 dS m^{-1} (well water). The EC of the shallow ground water ranged from 4.7 dS m^{-1} to 16.4 dS m^{-1}, depending on the particular field and time of year. Soil type was clay loam at the three sites. In addition, a small-plot randomized block replicated experiment was superimposed on each drip system with irrigation treatments consisting of different amounts of irrigation water to determine the minimum amount of water needed for maximum yield under saline, shallow ground water conditions.

At a fourth commercial field where saline, shallow ground water was about 0.45 m to 0.6 m deep, a small-scale randomized block replicated experiment evaluated the effect of applied water amounts on processing tomatoes and cotton yield. Drip irrigations occurred daily. The electrical conductivity of the irrigation water was 0.52 dS m^{-1}. The electrical conductivity of the shallow ground water ranged from 8 to 11 dS m^{-1}.

Computer Simulations

The computer simulation model HYDRUS-2D (Šimůnek et al., 1999) was used to evaluate leaching with subsurface drip irrigation under saline, shallow ground water conditions by simulating soil water and soil water salinity distributions around drip lines. Output of the simulations were the distributions of soil water, soil water salinity, and pressure head around the drip line; salt mass and volume of soil water in the profile; and amount of drainage below the root zone. This model has been previously used in studies of water and chemical movement under drip irrigation (Gardenas et al., 2005; Hanson et al., 2006).

System design characteristics used for the simulations were typical of the subsurface drip systems used for processing tomatoes. Drip line depth was 20 cm; emitter spacing was 30 cm; and low flow drip tape was used . A line-source model with a rectangular geometry was used because of the multiple closely-spaced outlets along the drip line. The model domain was the top 100 cm of a soil profile extending 75 cm from the drip line, which represents the area explored by roots based on field experience and measurements. The boundary condition along the sides of the domain was no water flux; the boundary condition at the bottom of the domain was constant pressure representing the position of the ground water table; an atmospheric boundary condition was used at the top of the domain. The constant pressure boundary at the bottom of the domain allowed water draining below the drip line to flow out of the domain without raising the water table, which provided an estimate of the potential leaching fraction below the root zone.

Simulations were conducted for water table depths of 0.5 and 1.0 m, irrigation water salinities of 0.3, 1.0, and 2.0 dS m^{-1}, and applied water amounts of 80, 100, and 115% of the potential evapotranspiration. For the EC = 0.3 dS m^{-1}, an additional water application of 60% was also conducted. Two irrigations per week occurred for the 1.0 m water table depth; daily irrigations occurred for the 0.5 m depth. EC's of shallow ground water were 10.0 dS m^{-1} and 8.0 dS m^{-1} for the 0.5 and 1.0 m water table depths, respectively, based on the field measurements. The initial soil water salinity levels at the start of the simulation period were based on field measurements. Simulations were conducted for a 42 day period.

RESULTS AND DISCUSSION

Field Experiments

Yields of the three large-scale subsurface drip systems exceeded those of sprinkle irrigation by 12.1 Mg ha^{-1} to 22.6 Mg ha^{-1} (Hanson & May, 2004). Average yields were 93.7 Mg ha^{-1} and 74.8 Mg ha^{-1} for subsurface drip irrigation and sprinkle irrigation, respectively, statistically significant for $\alpha = 0.05$ (t-test). Tomato yield was unaffected by the range of soil salinity levels measured in these fields, which ranged from levels smaller than the threshold level of 2.5 dS m^{-1} (Mass and Grattan, 1999) for tomatoes to levels exceeding the threshold soil salinity. (The threshold soil salinity, expressed as the electrical conductivity of the saturated extract, is the maximum root zone soil salinity at which no yield reductions occur.) The average difference in soluble solids between the two irrigation methods was not statistically significant. In the small plot experiments, yields decreased as applied water decreased and soluble solids increased as applied water decreased. Based on the average yield increase and a crop price of \$55 Mg^{-1}, drip irrigation increased profits by \$1284 ha^{-1} more than those under sprinkle irrigation.

At the fourth site, tomato yields in the small-scale randomized replicated experiment ranged from 77.5 Mg ha^{-1} for 396 mm of applied water to 95.9 Mg ha^{-1} for 589 mm of water (about equal to the seasonal evapotranspiration) (Hanson et al., 2006). The regression between yield and applied water was highly significant at a level of significance of 0.05 ($P = 0.0008$). Cotton yield was unaffected by amount of applied water for amounts equal to or greater than about 40% of the potential crop evapotranspiration.

Soil salinity levels around drip lines depended on depth to the ground water, salinity of the shallow ground water, salinity of the irrigation water, and amount of applied water. For water table depths of 2 m, soil salinity levels (expressed as the EC of a saturated extract) smaller than the threshold salinity occurred and were relatively uniform around the drip line (fig. 1A). For water table depths of less than 1 m, salinity varied considerably with the smallest levels near the drip line and highest near the periphery of the wetted volume (fig. 1B). Higher values of soil salinity occurred near the drip line for the higher EC irrigation water (fig. 1C). Larger water applications increased the zone of low salt soil around drip lines (fig. 2).

The key to the profitability and sustainability of subsurface drip irrigation under saline, shallow ground water conditions is salinity control. Salinity control requires leaching or flushing of salts from the root zone by applying irrigation water in excess of the soil moisture depletion. The leaching fraction, used to quantify leaching adequacy, is the ratio of the amount of water draining below the root zone to the amount applied.

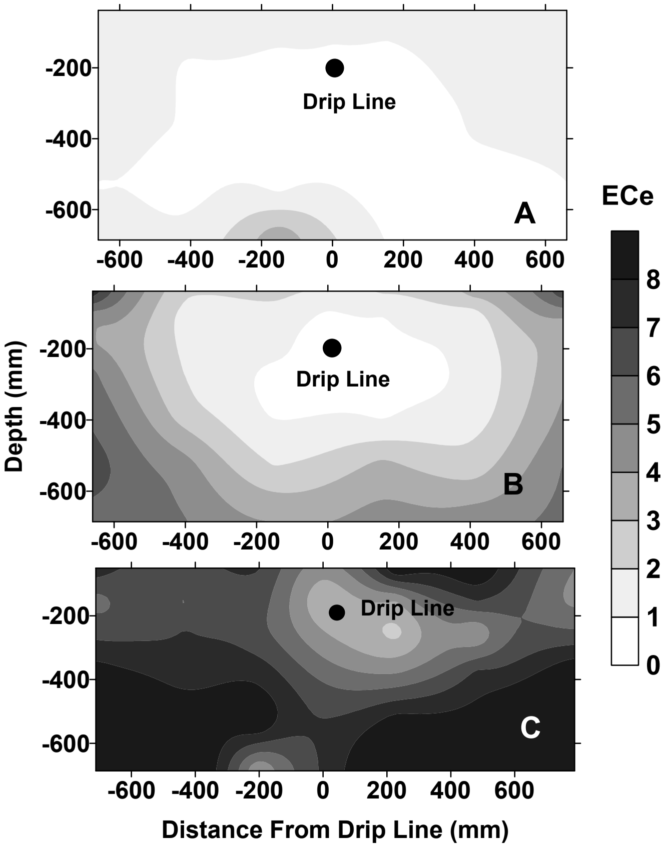

Figure 1. Patterns of soil salinity around drip lines for (A) an average water table depth = 2 m, EC of the irrigation water = 0.3 dS m^{-1}, and ground water EC = 8 to 11 dS m^{-1}; (B) water table depth between 0.61 and 1 m, EC of the irrigation water = 0.3 dS m^{-1}, and ground water EC = 5 to 7 dS m^{-1}; and (C) water table depth between 0.61 and 1 m, EC of the irrigation water = 1.1 dS m^{-1}, and ground water EC = 9 to 16 dS m^{-1}. The black dots are the drip line locations. Values are EC of saturated extracts (dS m^{-1}).

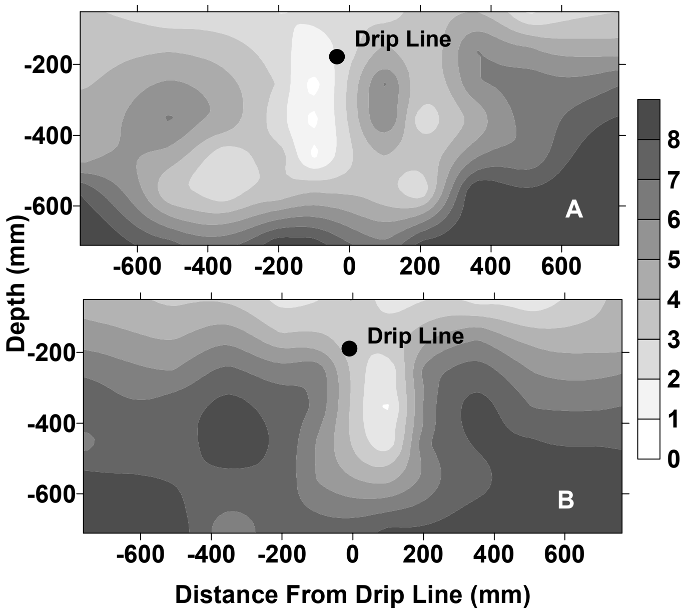

Figure 2. Effect of amount of applied irrigation water on the patterns of soil salinity around the drip line for (A) 589 mm of applied water (about equal to the seasonal evapotranspiration), and (B) 397 mm of applied water. EC of the irrigation water = 0.52 dS m^{-1} and the EC of the shallow ground water = 8 to 11 dS m^{-1}. The black dots are the drip line locations. Values are EC of saturated extracts (dS m^{-1}).

Leaching fractions can be determined several ways. One approach is to measure the average root zone soil salinity and the salinity of the irrigation water and then use appropriate charts or equations to determine the leaching fraction (Ayers and Westcott, 1985). However, because soil salinity, soil water content, and root density all vary around the drip line, some uncertainty exists in determining the average root zone salinity, and thus, leaching fraction, under drip irrigation.

A second approach commonly used is the water balance method which calculates the field-wide amount of leaching as the difference between seasonal amount of applied water (measured with a flow meter) and evapotranspiration. Field-wide leaching fractions were calculated for the commercial fields using the water balance approach. These calculations showed little or no field-wide leaching at most of the sites (table 1), suggesting the possibility of inadequate salinity control and raising questions about the sustainability of drip irrigation. The soil salinity data, however, clearly showed that because of the spatially varying wetting under drip irrigation, substantial leaching was occurring near the drip lines (referred to as localized leaching herein) and that the leaching was highly concentrated near the drip line. It is reasonable to expect that these salinity patterns reflect long-term patterns as long as adequate amounts of low salt irrigation water are applied and no ground water intrusion occurs into the root zone. The soil salinity data indicated that the water balance approach is not appropriate for drip irrigation.

Table 1. Seasonal applied water, evapotranspiration, and field-wide leaching fractions calculated from a water balance for the four commercial sites.

Year	Seasonal applied water (inches)	Seasonal evapotranspiration (inches)	Leaching fraction (%)
		BR	
1999	406	516	0
2000	427	544	0
2001	521	582	0
		DI	
1999	564	638	0
2000	737	640	13.1
2001	582	676	0
		DE	
2000	732	615	13.6
2001	561	587	0
		BR2	
2002	589	617	0

Computer Simulations

The simulated patterns of soil water salinity of the HYDRUS-2D model were similar to the soil salinity patterns found in the commercial fields, and showed that the soil was reclaimed rapidly under subsurface drip irrigation (fig. 3). The volume of reclaimed soil increased with time with most of the reclamation occurring below the drip line while salt accumulated above the drip line. The larger the amount of applied water, the larger the volume of reclaimed soil below the drip line (data not shown), behavior which is similar to that in Figure 2. However, the simulation data show that considerable leaching occurred around the drip line for water applications of 60 and 80 percent, normally considered to be deficit irrigation conditions with no field-wide leaching (data not shown).

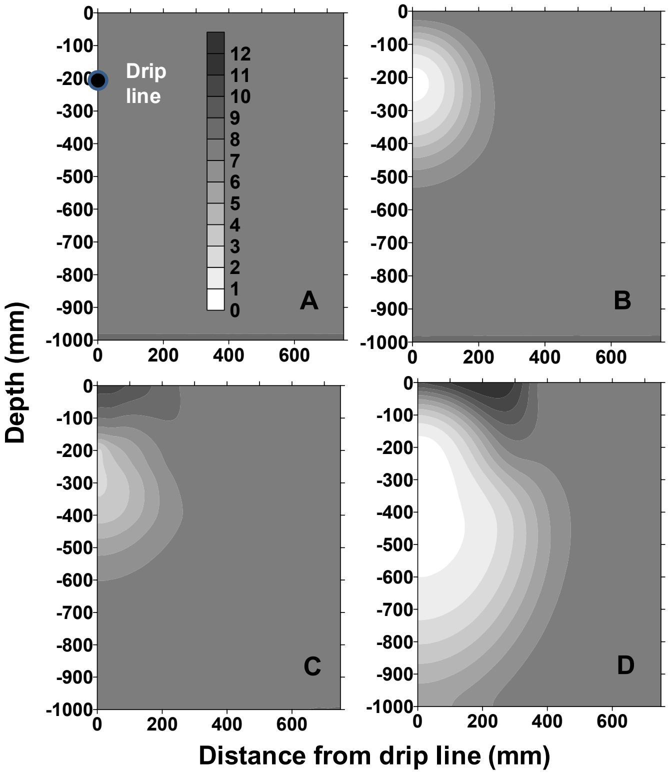

Figure 3. Simulated patterns of soil water salinity around drip lines for (A) prior to initiation of drip irrigation; (B) at the end of the first irrigation; (C) just before the second irrigation; and (D) at the end of the last irrigation. EC of the irrigation water = 0.3 dS m^{-1}; applied water = 100%; water table depth = 1.0 m.

Actual or localized leaching fractions ranged from 7.7% (60% water application) to 30.9% (115% water application), and was 24.5% for the 100% water application (table 2). As the salinity of the irrigation water increased, localized leaching fractions increased for a given amount of applied water because of reduced root water uptake. Thus, even for applications less than potential ET, considerable localized leaching occurred around the drip lines, reflecting the spatially-varying wetting around the drip line. This localized leaching is highly concentrated near the drip line, an area where root densities are likely to be the highest.

Table 2. Amount of applied water, root uptake, drainage (amount of water flowing out of the bottom of the domain), and localized leaching fraction (expressed as a percentage) for different amounts of applied water (expressed as a percentage of the potential crop evapotranspiration) and different irrigation water salinities (EC_i) for the simulated conditions. Water table depth was 1.0 m. Similar results occurred for the 0.5 m depth water table conditions.

Applied Water (%)	Applied water (cm^2)	Root uptake (cm^2)	Drainage (cm^2)	Leaching fraction (%)
		EC_i = 0.3 dS/m		
60	1410	1350	109	7.7
80	1890	1580	328	17.3
100	2360	1760	600	24.5
115	2710	1850	837	30.9
		EC_i = 1.0 dS/m		
80	1890	1440	431	22.8
100	2360	1610	719	30.4
115	2710	1700	962	35.4
		EC_i = 2.0 dS/m		
80	1890	1260	585	30.9
100	2360	1390	899	38.1
115	2710	1480	1150	42.4

CONCLUSIONS

Conclusions of both field research and computer simulation modeling are:

- Subsurface drip irrigation of processing tomatoes is highly profitable compared to sprinkle or furrow irrigation under saline, shallow ground water conditions.
- Tomato yield increased as applied water increased; cotton yield was unaffected by applied water amounts for water applications equal to or exceeding 40 percent of the potential evapotranspiration.
- Root uptake of the saline, shallow ground water by tomatoes should be minimized to prevent yield reductions; root uptake of the ground water by cotton should be encouraged.
- Considerable localized leaching occurs under subsurface drip irrigation due to the spatially-varying wetting around drip lines. The localized or actual leaching fraction was about 25% for a water application equal to 100% of the potential evapotranspiration.
- The localized leaching is highly concentrated near the drip line, resulting in relatively low soil salinity levels in the area where root density has been found to be the highest under subsurface drip irrigation of processing tomatoes.
- The water balance approach is inappropriate for estimating leaching fractions under drip irrigation.
- Little water table response to drip irrigation occurred except when overirrigation occurred.

- Reclamation around newly installed drip lines in saline soil was rapid. The reclamation was faster for relatively large water applications per irrigation applied less frequently than for smaller applications per irrigation applied more frequently.
- The low salt zone around the drip line increased as the amount of applied water increased.
- Soil salinity around the drip line increased as the salinity of the irrigation water increased.
- Very high irrigation efficiencies under drip irrigation can only be obtained by substantial deficit irrigation. This contrasts the assumption frequently made that drip irrigation is nearly 100% efficient for water applications equal to about 100% of the potential evapotranspiration.

The key factor for sustainable drip irrigation is profitability through adequate salinity control. Based on these experiments and simulations, recommended practices for sustainable subsurface drip irrigation of processing tomatoes under saline, shallow ground water conditions include:

- Seasonal water applications should be about equal to the seasonal crop water use. This water application appears to provide sufficient localized leaching. Higher applications could cause ground water intrusion into the root zone; smaller applications will decrease tomato yield.
- Salinity of the irrigation water should be equal to or smaller than about 1 dS m^{-1}.
- Daily to two to three irrigations per week should occur. High frequency irrigations will minimize root uptake of the saline ground water.
- Periodic leaching of salt accumulated above the buried drip lines will be necessary with sprinklers for stand establishment if winter and spring rainfall is insufficient to leach these salts.
- Drip irrigation systems must be designed for high field-wide uniformity of applied water.
- Periodic system maintenance must be performed to prevent clogging of drip lines.

Can drip irrigation eliminate the need for subsurface drainage systems and drainage water disposal methods? No subsurface drainage systems were used at these sites, and no trend in yield with water table depth or soil salinity occurred. Subsurface drip irrigation continues to be used at this time at these sites along with many other fields along the west side.

Little response of the water table to drip irrigation occurred at these sites except at one site where overirrigation occurred early in the year for one year. Reducing the applied water at this site caused the water table to decline. Although drainage below the root zone occurred under subsurface drip irrigation, as shown by the simulations, the amount of drainage per irrigation was small because of the small water applications per irrigation, and because of the high irrigation frequency, its distribution over time was relatively uniform. As a result, the natural subsurface drainage in these fields appeared to be sufficient to prevent ground water intrusion into the root zone. This behavior suggests that, for the conditions found in these fields, subsurface drainage systems and drainage water disposal methods are not needed for properly managed and designed drip irrigation systems. For locations where the water table is affected by drip irrigation, subsurface drainage systems and disposal methods may be required.

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