LEACHING OF ACCUMULATED SOIL SALINITY UNDER DRIP IRRIGATION

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ABSTRACT. *ITRC conducted a reclamation leaching experiment in a drip-irrigated pistachio orchard south of Huron, California, during the winter of 2002-2003. The study was conducted to quantify the leaching water required to remove salts from the effective root zone of trees. This experiment tested a new reclamation leaching technique: multiple lines of low-flow drip tape were used to apply water to the area of salinity accumulation along a tree row. This new technique allows water to be applied where there is salt accumulation along the tree row, as opposed to putting water on the entire area of the field. Since reclamation leaching requires a relatively large depth of water, this technique offers the potential for significant water savings for reclamation leaching.*

Keywords. *Drip irrigation, Emitters, Leaching, Salinity, Salt, Soil.*

This soil salinity reclamation leaching experiment was prompted by the results from a separate salinity accumulation study (Burt and Isbell, 2003) that was completed by the Irrigation Training and Research Center (ITRC) of California Polytechnic State University, San Luis Obispo, during the summer of 2002. The findings of the salinity accumulation study indicated that in arid and semi-arid regions the salt accumulation in the root zone can indeed be a concern for farmers irrigating tree crops with drip irrigation systems, especially when an orchard is replanted. ITRC observed that deep percolation with a standard drip system still leaves significant amounts of salt in the soil along a tree row.

In general, irrigating with wastewater or saline irrigation water presents specific risks. Among these risks are soil salinization and salinity hazards due to salt accumulation in the root zone, especially in areas affected by under-irrigation (Pereira et al., 2002). Although saline soil can produce acceptable yields (Oron et al., 1999), excessively saline irrigation water leads to reduced water available for plant use, which in turn can result in lower stem diameter and subsequently, lower fruit yield. In order to compensate for the salt accumulation, irrigation with highly saline water requires larger and more frequent applications than irrigation with good quality water (Boman and Stover, 2002).

There are many simultaneous processes involved in salt movement in soil, which make accumulation patterns and leaching practices difficult to calculate mathematically (Oster et al., 1999). A number of factors must be taken into account, such as soil hydraulic properties, crop species and root distribution patterns, emitter flow rate, irrigation water salinity, effective rainfall, spacing, and tillage depth patterns (Oron et al., 1999, Pereira et al., 2002).

The classic explanation of leaching effectiveness by Hoffman (1986) describes vertical leaching in soils. Leaching with closely spaced furrows, sprinkler irrigation on row crops, and border strip and basin irrigation (if on non-cracking soils, and ignoring preferential flow) is approximately vertical. Hoffman showed that the effectiveness of vertical leaching depends on the percentage of deep percolation, the soil, and the rate at which water infiltrates into the soil. In particular, he noted that intermittent ponding was more effective in salt leaching than was continuous ponding.

PROCEDURES

The leaching experiment was conducted in a pistachio orchard on the west side of the San Joaquin Valley, California, a region with a semi-arid climate. Specific information about the selected field is given in table 1.

The soil in the study area is relatively uniform, of the Westhaven series, with silt-loam being the most predominant texture. The available water holding capacity of the soil, as classified by NRCS soil surveys (USDA-NRCS, 2003) was approximately 19 cm of water per meter of soil. The Westhaven series consists of very deep soils that formed in stratified mixed alluvium weathered from sedimentary and/or igneous rock and deposited on alluvial fans and flood plains. These soils are well drained, have low runoff, and moderately slow permeability. The slope is 1.4% in the orchard.

Table 1. Field and irrigation system information for leaching study.

Crop:	Pistachio	Irrigation system:	Drip
Year planted:	1982	Installation date:	1982
Field size:	63 ha	Number of hoses:	2
Layout pattern:	Diamond	Emitter spacing:	1.7 m
Row spacing:	5.8 m	Nominal flow rate:	1.9 L h^{-1}
Tree spacing:	6.7 m	Wetted area:	0.8 m dia.

Article was submitted for review in January 2004; approved for publication by the Soil & Water Division of ASABE in October 2005.

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Table 2. Irrigation history summary (from 1982 to 2002).

	Irrigation Water (m)			Water Quality, ECw[a] ($dS\ m^{-1}$)		Weighted ECw ($dS\ m^{-1}$)
	Surface	Well	Total	Surface	Well	
Total	8.15	3.88	12.03			
Weighted average				0.45	1.23	0.70

[a] ECw = electrical conductivity of the irrigation water.

Since the trees were planted in 1982, UN-32 fertilizer has been applied to the field through the drip irrigation system once or twice per month during the peak growing season, for a total of six to eight applications per year. During each application, approximately 22 kg ha^{-1} of UN-32 was applied.

The orchard is irrigated with both groundwater and surface water from the Westlands Water District. The percentage of groundwater versus surface water applied during an irrigation season has varied. Table 2 presents the irrigation water totals since 1982.

Included in the total irrigation water are the winter irrigations, supplied by surface water. The average annual precipitation, according to precipitation data recorded at California Irrigation Management Information System (CIMIS, 2003) station 2 (Five Points) and station 15 (Stratford), has been approximately 220 mm $year^{-1}$ since 1985. However, several years in the 1990s had rainfall amounts significantly greater than the average. Annual rainfalls for the mid-1990s were: 240 mm in 1992, 260 mm in 1994, 210 mm in 1995, and 270 mm in 1996.

Even though the weighted average salinity of the irrigation water (ECw) since 1982 is 0.70 dS m^{-1}, during the four years prior to the leaching study most of the irrigation water applied was well water with ECw of 1.23 dS m^{-1}.

SALINITY ACCUMULATION PRIOR TO LEACHING EXPERIMENT

Figure 1 shows a soil salinity profile spanning two rows of trees, which was measured in the field in the summer of 2002. These profiles showed high salinity concentrations along the tree rows in a 1.5 m root zone. The average ECe before the trees were planted was approximately 1.12 dS m^{-1}. Since the trees were planted, the average ECe across the profile from the middle of one bed to the middle of another (5.8 m), to a soil depth of 1.5 m, has increased from 1.1 dS m^{-1} to 3.6 dS m^{-1}. Likewise, the average root zone ECe along the tree row has increased from 1.1 dS m^{-1} to approximately 5.7 dS m^{-1}.

The results of a salt balance showed that only approximately 1/3 of the salt applied through irrigation water remained in the 1.5 m deep root zone profile before the leaching trials. This indicates that approximately 2/3 of the salt had been leached prior to the experiment. In addition, soil moisture contents 2.4 m deep (below the root zone) near the tree rows were higher than those between the tree rows, which also suggests that leaching had occurred.

It is unrealistic to assume that one can use farm irrigation and weather data over the past 20 years to predict leaching volumes within a few percentage points. An average ECe of 3.6 dS m^{-1}, with the weighted ECw, indicates about 4% leaching fraction. Recognizing that typical farm irrigation includes occasional over-irrigation as well as under-irrigation, and observing a moist soil below the root zone, we believe that 4% under-estimates the actual leaching fraction. Regardless of those numbers, leaching with a standard drip system cannot be as effective as leaching with sprinklers or furrows because the edges of the wetted area are not leached, but instead accumulate salt in arid areas (fig. 1). Due to this, if complete reclamation leaching on orchard drip systems is needed, it must be done with some irrigation method other than the drip system.

METHODS AND PROCEDURES

SOIL SAMPLING

A direct-push type, hydraulically powered soil sampler (model 9800E, Concord Environmental Equipment, Hawley, Minn.) was used to collect soil cores. Before leaching and after each leaching event, soil samples were removed at six locations along the tree row. At each location, seven 2.4 m deep soil cores were removed. The seven cores were spaced 0.3 m apart, perpendicular to the drip hoses. To establish a

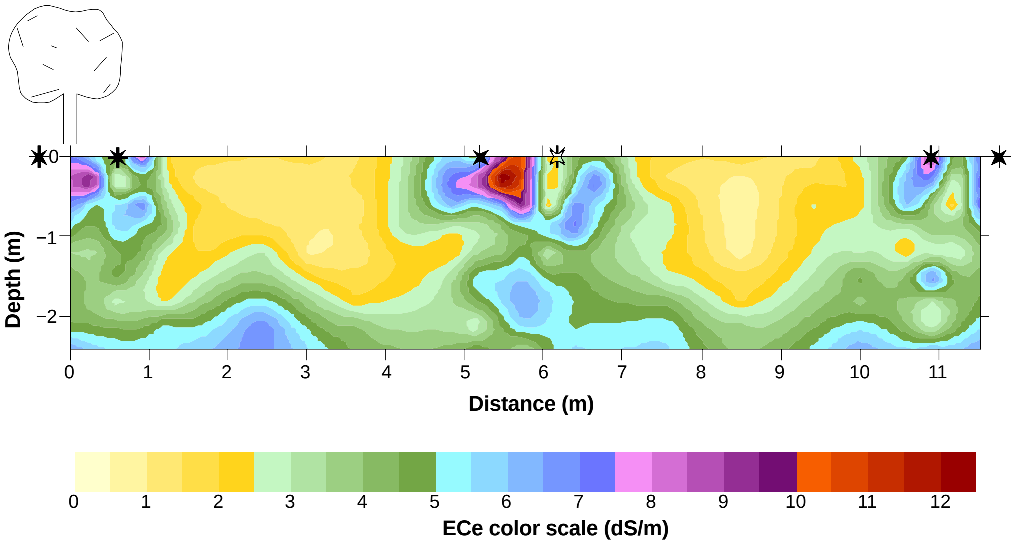

Figure 1. Typical salinity concentration profile in the field where the reclamation leaching study was conducted (ECe = electrical conductivity of a saturated paste extract; * indicates the location of emitters).

consistent point of reference, each sampling location intersected a drip emitter.

Nine individual soil samples were collected from each 2.4 m core at increments of 0.3 m, starting at the surface and ending at a depth of 2.4 m, for a total of 63 samples per soil profile. One tube was used for retrieving soil to a depth of 1.2 m; a separate tube was used for retrieving a soil core to 2.4 m below the soil surface. A new clear plastic tube was used for each core that was removed. Approximately 300 g of soil were collected for each sample to be tested. Each soil sample was sealed in a plastic bag and labeled according to the specific location where it was taken. Just prior to bagging, the approximate soil moisture content for each soil sample was determined using the "feel" method and recorded.

An EM38 instrument (Geonics, Ltd., Mississauga, Ontario), which uses electromagnetic induction as a non-invasive method to determine the electrical conductivity of the soil, was also used to take some trial EC measurements in the field after the first leaching. However, it was found that the values obtained with the EM38 were insufficiently distinct (with distance) to trace salinity movement through individual soil layers. Therefore, those results are not presented in this article.

The ECe values were determined in a laboratory. For each sample, approximately 100 g of soil for ECe measurement was dried, ground, passed through a 10-mesh screen, and saturated with distilled water for 24 h. Several milliliters of solution were extracted through a No. 1 Whitman paper filter in Buchner funnels with a vacuum system. A drop of 0.1% $Na(PO_3)_6$ was added to the extract to prevent calcium carbonate precipitation. The electrical conductivity of the saturated paste extract (ECe) was measured using a calibrated, temperature-compensating, digital readout conductivity instrument (model 3200, YSI, Inc., Yellow Springs, Ohio).

LEACHING EXPERIMENT DESIGN

This study tested a new idea for the application of reclamation leaching water. Normally, sprinklers or furrows are used for reclamation leaching, so that water is applied over the whole field. However, with drip irrigation, salinity buildup is mainly a problem along the tree rows. Therefore, leaching water should not have to be applied to the whole field, just to the problem areas. In this case, water was applied to 1/3 of the field area, requiring only approximately 1/3 the amount of leaching water when compared to conventional leaching techniques. This is significant since reclamation leaching requires a large depth of water.

To specifically target the areas of salt buildup, drip tape was used to apply the leaching water in this experiment, instead of sprinklers. Six lines of closely spaced low-flow drip tape were placed along one row of trees (30 trees total) to apply leaching water to the soil area that had salt accumulation (fig. 2). Three lines of drip tape were placed on either side of the tree. The spacing between the drip lines was 0.305 m. The emitter spacing was also 0.305 m along the tapes. The nominal (but not actual) flow of the drip tape was 164 L h^{-1} per 100 m. The actual average application rate during leaching was approximately 5.8 mm h^{-1}. This management was intended to achieve high leaching efficiency (i.e., remove the maximum salt possible per unit of leaching water) by using intermittent leaching with continuously unsaturated conditions on the soil surface, although in fact there was some surface ponding.

Figure 2. Low-flow drip tapes, spaced 0.30 m apart, used to apply the leaching water.

The leaching water was surface water taken from a Westlands Water District turnout. The water was filtered through a media tank that was part of the farmer's system and then through an additional 150-mesh screen filter. A 103 kPa pressure regulator was installed just downstream of the screen filter to control the drip tape pressure and flow rate. A 1.6 cm magnetic-drive flowmeter (PMM Multi-Jet, Invensys Metering Systems, Uniontown, Pa.) was used to measure the quantity of leaching water applied.

During a typical leaching event, water was applied for approximately 24 h, turned off for several days, and then turned back on for approximately 24 h. The soil was undisturbed for at least five days after the leaching water was applied before soil samples were collected.

Leaching water was applied four times; total cumulative net infiltration (subtracted estimated evaporation and adding precipitation) was 666 mm. The soil surface was glossy, and there was some ponding on the soil surface, but no horizontal soil surface translocation of irrigation water was observed.

This research had one application rate, with six replications (locations). The soil sampling was destructive in nature, which inherently contributes to errors when one attempts to track changes over time. Furthermore, the large variability in salt concentrations seen in figure 1 illustrates the difficulty in obtaining precise trends in field salinity research. The authors feel that the large number of soil samples (6 locations × 5 sampling events × 7 cores/location × 9 samples/core = 1890 samples) analyzed, plus the consistency seen in the graphical trends, provided reasonable results for an irrigation practice that has not been previously examined.

RESULTS

LEACHING WATER MOVEMENT AND DESTINATIONS

For each leaching event, the soil moisture values (estimated using the "feel" method) at the six locations were averaged according to the soil profile grid. That is, for a specific coordinate on the soil profile, six values were averaged. These average soil moistures were plotted (fig. 3).

After the fourth leaching, the entire 2.4 m soil profile was at field capacity, so that graph is not included in figure 3. Plots of the soil moisture profiles indicated relatively uniform movement of leaching water down through the soil layers. This is substantiated by two observations:

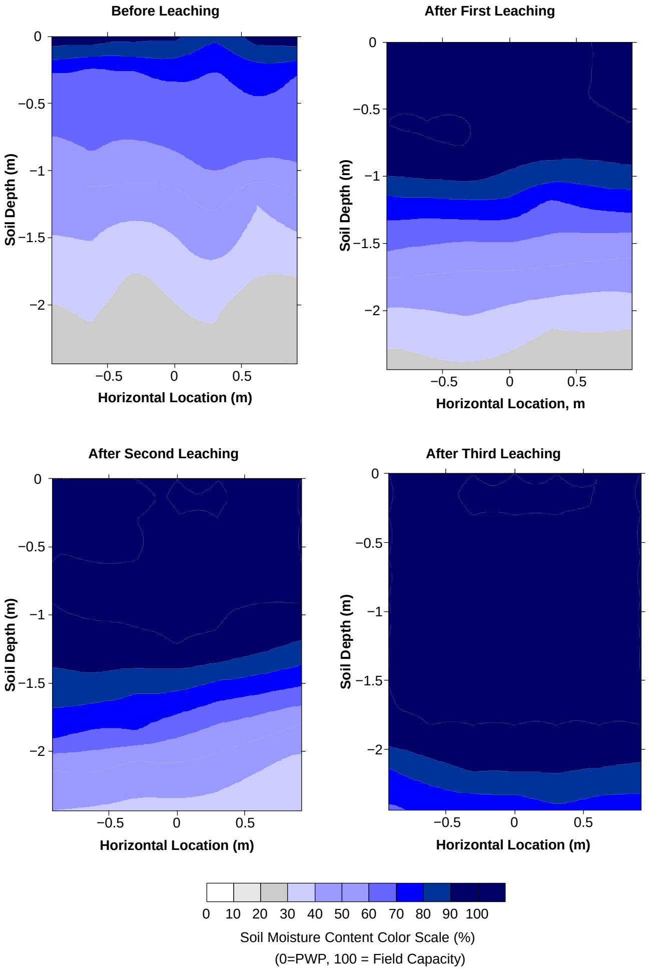

Figure 3. Soil moisture profiles before and during the leaching experiment.

- After the first leaching, the distance between soil moisture content contours remains very similar; the levels of different soil moistures move down in the soil profile uniformly.
- The contours are relatively horizontal across the profile. This suggests that there was minimal lateral movement of leaching water.

The plots also show some movement of water into lower soil layers before those above were at field capacity.

After the fourth leaching (cumulative net infiltration = 666 mm), several soil cores were also removed between the tree rows to check the lateral movement of leaching water. Leaching water had moved approximately 0.9 m beyond the leaching study boundary on each side.

AVERAGE ELECTRICAL CONDUCTIVITY

To compare the salinity concentration patterns in the soil profile after successive applications of leaching water, the average ECe values were plotted in Surfer 8.02 (Golden Software, Inc., Golden, Colo.). Only coordinates from the five inner soil cores in the soil profile were considered (fig. 4). The average electrical conductivity plots have a similar format to the soil moisture content plots. The profiles represent an area 1.2 m horizontally and a soil depth of 2.4 m. The horizontal location labeled “0” is in line with the tree row.

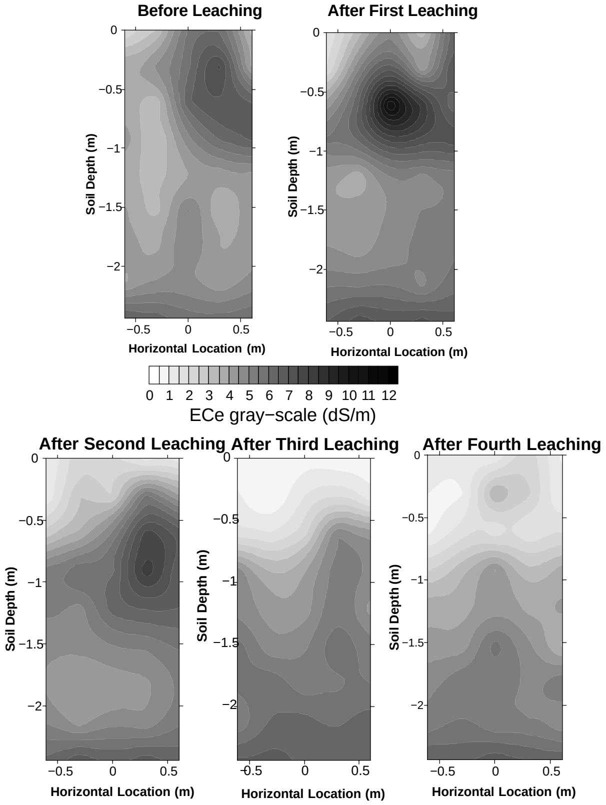

Figure 4. Average ECe profiles.

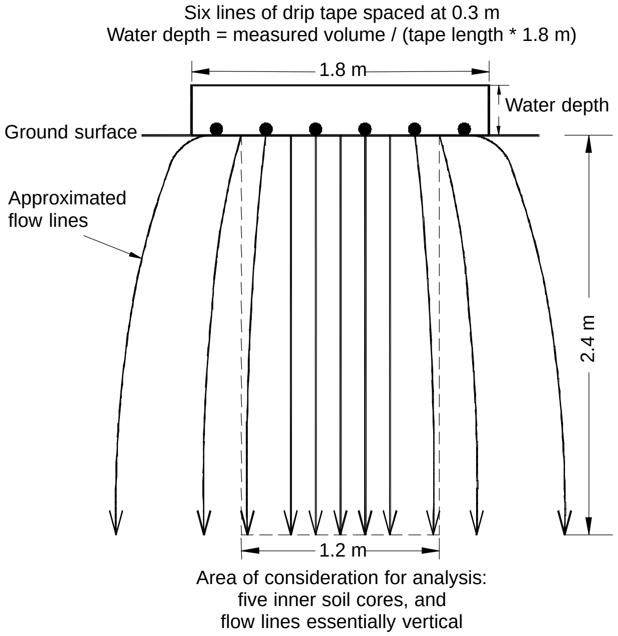

Figure 5. Water movement through the area of consideration.

In general, the plots of the average saturated ECe throughout the soil profile during various stages of leaching show that salt concentration throughout the 2.4 m deep soil profile decreases after each leaching. The layer of low ECe values expands with successive leaching water applications. In addition, pockets of high salt concentration that were present initially were dispersed. With time, stratified layers

Table 3. Summary of soil sample collection and the quantity of net infiltration.

Date of Irrigation and Subsequent Soil Sampling (2003)	Irrigation Water Applied (cm)	Precipitation Since Last Leaching (cm)	Evaporation Since Last Leaching (cm)	Net Infiltration (cm)	Cumulative Net Infiltration (cm)
9 January	9.6	−−	−−	9.6	9.6
14 January	Soil samples collected after 1st leaching				
17 January	9.3	0.6	0.5	9.4	19.0
23 January	Soil samples collected after 2nd leaching				
24 January	13.4	0.0	0.4	13.0	32.0
29 January	12.7	0.0	0.5	12.2	44.2
6 February	Soil samples collected after 3rd leaching				
7 February	13.0	0.0	1.4	11.6	55.8
19 February	11.2	1.7	2.1	10.8	66.6
27 February	Soil samples collected after 4th leaching				

of lower salinity concentrations developed down through the soil profile.

RECLAMATION LEACHING WATER AND SALINITY REDUCTION

The gross depth of leaching water applied to the area of consideration was calculated by dividing the measured volume of water applied by the total area of the leaching study (width of 1.8 m and length of 83.8 m). The "area of consideration" was the area in which primarily vertical water movement occurred, which was assumed to be below the five inner soil cores, an area 1.2 m wide (fig. 5). It is assumed that any lateral movement of leaching water outside of the boundary originated from the outermost drip tapes.

The net infiltration for the area of consideration was then determined as follows:

$$\textit{Net infiltration of the water applied} = \textit{Depth of leaching water applied} + \textit{Precipitation since the last leaching} - \textit{ETo since the last leaching.}$$

in which the evaporation was assumed to be equal to the grass reference evapotranspiration because the soil surface was continually wet, the trees were dormant, and there was no weed growth.

The average daily reference evapotranspiration (ETo) was calculated with the FAO-56 Modified Penman-Monteith equation using CIMIS data. The net infiltration during each leaching event and the cumulative net infiltration are given in table 3. The third and fourth leaching applications were divided into two sets to minimize surface runoff.

To evaluate the reduction of the average salinity for a certain soil zone, the net leaching water that percolated through that soil layer was considered. Specifically, the change in soil moisture storage of a soil zone was subtracted from the net amount of water infiltrated to find the net amount of leaching water that percolated through that soil zone:

Table 4. Cumulative depth of net leaching water for each soil zone.

Soil Zone (m)	Cumulative Depth of Net Leaching Water through Each Soil Zone after Each Leaching Event (cm)			
	1st	2nd	3rd	4th
0 to 0.3	8.5	18.0	43.2	65.5
0 to 0.6	6.6	16.1	41.3	63.6
0 to 0.9	4.4	13.9	39.1	61.4
0 to 1.2	1.8	11.3	36.5	58.8
0 to 1.5	0.0	8.0	33.2	55.5
0 to 1.8	0.0	4.3	29.5	51.8
0 to 2.1	0.0	0.2	25.4	47.7
0 to 2.4	0.0	0.0	21.2	43.5

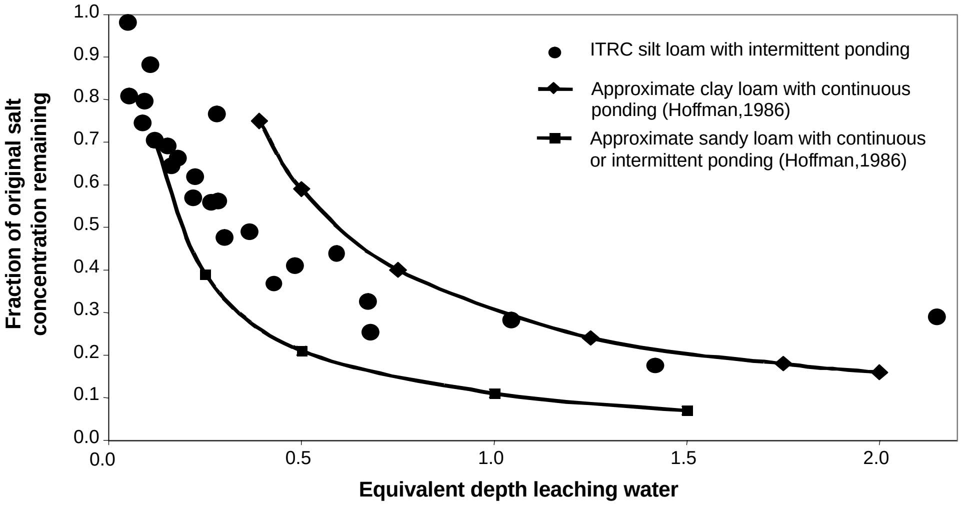

Figure 6. Relationship between the equivalent depth of leaching water and the fraction of initial salt content, considering five inner soil cores (modified).

Net leaching water of a soil layer=

Net infiltrated into that soil zone

− Depth of water required to bring

that soil zone to field capacity.

Since the root zone was not at field capacity when leaching water was initially applied, different depths of net leaching water percolated through each soil zone (table 4).

After each leaching, the new weighted average salt content in each area of consideration was also calculated. Four of the six sample locations were chosen as the most representative of salinity concentration patterns. ECe values from the five inner vertical cores at each sample location were used. The ECe values were then averaged and weighted according to their position in the salinity profile grid. The change in soil salinity content was then plotted against the equivalent depth of leaching water (fig. 6).

The fraction of the initial salt content remaining was defined as the new average soil zone ECe divided by the initial average ECe for that soil zone. Our data showed that our initial sampled average ECe benchmarks (shown in fig. 3) were too low because the average soil zone ECe in some sample locations, after the first leaching, were higher than before leaching. Such a discrepancy can occur because the soil sampling is destructive, and this variability clearly illustrates the difficulty of obtaining highly accurate statistical relationships in this type of study. Based on the theory that no average soil zone ECe should increase above the original average soil zone ECe, the initial ECe values were increased by 20% to develop a more realistic relationship curve seen in figure 6.

Equivalent depth of leaching water was defined as the depth of net leaching water divided by the depth of a soil zone (each having the same units). For example, one equivalent depth of leaching water for a 1 m soil zone was 1 m of net leaching water that percolated through that soil zone (because the change in soil moisture storage for that soil layer must be considered, the net water infiltrated would be greater than 1 m). Water that was stored in the soil zone was not net leaching water for that zone.

The relationship between equivalent depth of leaching water and the fraction of original salt content for a soil zone is shown in figure 6. Included in figure 6 are the approximate curves for the same relationship developed by Hoffman (1986). Based on figure 6, the approximate reductions in average soil zone ECe values for a range of leaching equivalent depths are shown in table 5. It should be noted that the depth of irrigation water applied for leaching must be greater than the leaching water because some of the applied water goes to soil moisture storage and evapotranspiration during reclamation.

Table 5. Approximate salinity reductions for various leaching equivalent depths (silt loam).

Equivalent Leaching Depth	Approximate Fraction of Original Salt Concentration Remaining
0.2	0.80 to 0.60
0.4	0.57 to 0.38
0.6	0.43 to 0.28
0.8	0.36 to 0.23
1.0	0.30 to 0.20

MAXIMUM EFFICIENCY OF LEACHING TECHNIQUES

In a field experiment conducted on a silty clay soil by Oster et al. (1973), the observed order of leaching efficiency was as follows: intermittent ponding > sprinkler > continuous ponding. Even though our experiment used low-flow drip tape and intermittent applications, the relatively high application rate (5.8 mm h^{-1}) caused some surface water ponding. Accordingly, the time-averaged water content within the depth wetted by drip irrigation was higher than under intermittent ponding. This counteracts the effects of reduced bypass flow and increased water content. Since there was some ponding in this experiment, it seems reasonable to find the curve for silt loam between clay loam with continuous ponding and the intermittent ponding curves developed by Hoffman (1986).

RELATIVE LEACHING EFFICIENCY

The salt reduction/equivalent leaching depth curve (fig. 6) illustrates that as more leaching water is applied, the amount of salt removed per unit depth of leaching water decreases. In this case, the slope of a line tangent to the salt reduction/leaching curve represents the fraction of salt removed per unit depth of leaching water. Table 6 contains the relative leaching efficiencies for various equivalent depths of leaching water applied, derived from the slopes of tangent lines for a range of equivalent depths. The values in table 6 suggest that leaching quantities greater than 0.8 equivalent depths result in insignificant salt reduction.

SUMMARY AND CONCLUSION

Leaching can reclaim salt buildup that would cause poor crop health and reduced plant vigor, especially when a new crop is planted. The leaching study revealed that, for tree crops:

- Irrigation with a typical orchard drip system in an arid or semi-arid area can develop highly saline areas on the edges of the wetted area.
- The practice of reclamation leaching using multiple, closely spaced drip tapes allows water to be applied directly to the areas of salt accumulation, as opposed to applying water to the entire field. In this case, water was applied to 1/3 of the field area, requiring perhaps half the amount of leaching water (accounting for edge effects) when compared to conventional leaching techniques. This is significant since reclamation leaching requires a large depth of water.

Table 6. Relative leaching efficiencies for various equivalent depths of leaching water.

Equivalent Depth	Relative Leaching Efficiency (%)
0.1	100
0.2	38
0.3	21
0.4	14
0.5	10
0.6	8
0.7	6
0.8	5
0.9	4
1.0	4

- There is a relationship between the equivalent depth of leaching water and the fraction of initial salt concentration that remains. The results from this experiment on a silt loam soil are summarized in table 6. It is important to note that the depth of irrigation water applied for leaching must be greater than the leaching water because some of the applied water goes to soil moisture storage and evapotranspiration during reclamation.
- The salt reduction/leaching depth relationship was similar to that found by Hoffman (1986).

There was no attempt in this experiment to establish whether the trees in this field were negatively impacted by the soil salinity accumulation. But salinity buildup becomes particularly important when trees are removed and the field is replanted with salt-sensitive crops. The most effective and efficient reclamation leaching practices for tree crops irrigated with drip appear to include:

1. Apply leaching water only to the areas with salt accumulation, typically along the tree row with drip lines.
2. Use low application rates for maximum effectiveness of salt removal.
3. Multiple lines of low-flow drip tape can be used to achieve 1 and 2.
4. Consider the point of diminishing effectiveness for reclamation leaching: quantities of leaching water greater than 0.8 equivalent depth may result in insignificant salt reduction (for a typical silt loam soil using intermittent leaching).
5. Use intermittent applications of leaching water, which minimize the effects of bypass flow.

ACKNOWLEDGEMENTS

Funding for this study was provided by Cal Poly State University, using funds of the California State University Agricultural Research Initiative and the California Department of Water Resources. The authors express sincere appreciation to Gary Robinson for providing the use of his pistachio orchard and for his support of the project.

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