Solutions
Project Report

A Cooperative Investigation by
the Santa Clara Valley Water District,
the City of Mountain View
and South Bay Water Recycling

City of Mountain View

Santa Clara Valley Water District

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The Santa Clara Valley Water District engaged researchers from the University of California to investigate soil and plant constraints on the quality of recycled water, and propose water qualities and management practices that would enable sustainable use of those waters. In early 2005, the District funded three projects to support these goals: 1. A survey of soil salinity using electromagnetic induction, done in April 2005, at Shoreline Links and Villages Golf Course to bench mark existing salinity conditions; 2. Soil studies to determine the impacts of water quality on soil hydraulic properties; and 3. Plant studies to determine the salt tolerance of coastal redwood.

The major finding of these projects was that coastal redwood, *Sequoia sempervirens* 'Aptos Blue', is sensitive to total soil-water salinity independent of the type of salt causing the salinity. Tree growth and leaf burn were affected equally by sodium chloride, calcium chloride, sodium sulfate, and a mix of sodium and calcium chloride. Soil-water salinities up to 1 dS/m[1] did not affect growth of 18-month old coastal redwood, whereas salinities of 3 dS/m resulted in reduced growth and noticeable leaf tip damage. At 6 dS/m, most of the leaves were dead. Based on these data, the goal of sustainable water management for redwoods would be to maintain soil-water salinity levels in the root zone between 1 and 2 dS/m and to allow levels to approach 3 dS/m only with great caution and intensive monitoring of both the soil and the leaf burn of redwood trees. The sensitivity of coastal redwood is the critical factor in determining the limits on the salinity of the applied water. Cool-season turf grass species are considerably more salt tolerant.

Long-term, sustainable irrigation of redwoods with waters that have salinity levels of 1 dS/m may be possible. However, considerable excess water over that consumed by the plants will need to be applied, and all of it must infiltrate into the soil to prevent soil-water salinity levels from exceeding 2 to 3 dS/m. For example, if the daily water requirement of a tree in June were 40 gal., 50 to 55 gal. will need to be applied.

Careful water management will be required, making full use of the following techniques: 1. Calculate the amounts of water to apply using measured reference evapotranspiration and the crop coefficient method of the California Irrigation Management Information System (CIMIS). 2. Apply the water beneath the tree canopy. 3. Monitor the soil water content in the root zone. 4. Apply sufficient water to maintain soil water contents at targeted levels. 5. Periodically adjust the crop coefficient so that the targeted soil water contents are achieved. 6. Determine the soil-water salinity in the root zone in March and September, and use these salinity levels to adjust the amounts of water to apply.

Soil salinity measurements become the primary feedback information to adjust the amount of irrigation water that needs to be applied. Since salinity takes from several months, at shallow depths in the root zone, to years at deep depths to adjust to changes in water management, it will take several years to fine tune irrigation management to prevent soil-water salinities from exceeding 2.5 to 3.0 dS/m.

Gypsum may need to be applied beneath the tree canopies to increase salinity and reduce sodium levels in the soil. Both changes can improve infiltration rates. The need for gypsum will be evident if infiltration rates are too slow and runoff occurs, or if the soils become so wet that aeration becomes limiting. Using gypsum will increase soil salinity over what will occur due to using recycled water alone. Since, as mentioned above, all sources of salt are equally effective in causing leaf burn of redwood leaves and in reducing growth, gypsum needs to be used sparingly, and attention needs to be paid to applying gypsum when it will be most effective. The best time to apply gypsum would be before the rain season begins. This will take advantage of several factors: 1. It will prevent low soil salinities developing at the soil surface as a result of leaching by rain, which is an important consideration because water flow rates in saturated soils were significantly reduced at low salinities in the soil studies conducted at University of California at Davis. 2. It will reduce sodium levels in the soil near the soil surface. 3. Salinity effects on plants will be minimized during the winter because of low temperatures and high humidities.

With even the best management, excess salinities may not be preventable. If so, there are two choices – reduce the salinity of the applied water, or remove the diseased redwood trees. Since salinity damage to trees is difficult to reverse, it may be that a reduction in salinity of the applied water, once recycled water has been used for several years, will not be effective in saving trees.

Soil salinity was determined in August 2007 at three locations: Shoreline Links, the Villages Golf Course and Wilson School. As expected each location poses different management problems.

At Shoreline Links, a clay cap that covers an underlying land fill prevents leaching through application and infiltration of more water than needed by the turf. Consequently, switching from existing water sources to water of greater salt content is not recommended unless extensive and effective provisions are made to provide drainage.

At the Villages, control of salinity in the fairways is occurring by leaching. The proportion of water leached is low, about 0.10, but adequate for turf grass. If the same is occurring under the redwoods, it is too low. The salinity of the water applied under the tree canopies should not exceed 1 dS/m, and the amount of applied water needs to be based on CIMIS reference evapotranspiration and adjusted as needed based on soil-based measurements in the rootzone of water content, or matric potential, and salinity.

At Wilson Adult School there is no permanent irrigation system beneath the tree canopy. One needs to be installed, and the salinity of the applied water should not exceed 1 dS/m. Determination of the amount of water to apply beneath the tree canopy should use the same procedures as those recommended above. On the turfgrass, South Bay recycled water and existing water management can continue to be used.

[1] A decisiemen/meter (dS/m) is a measure of electrical conductivity, and approximates to 640 ppm of salt.

IRRIGATION WITH RECYCLED WATER IN SANTA CLARA COUNTY: LIMITATIONS AND POTENTIALS

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1.0 INTRODUCTION

The Santa Clara Valley Water District (SCVWD) provided research funds to the University of California to assess appropriate treatment levels for recycled waters to be used for irrigation of landscapes throughout Santa Clara County. Studies were done at the University of California at Davis to determine the impact of water quality on Coastal Redwood and on soil hydraulic properties. The primary water quality parameters in these studies were electrical conductivity (EC) and sodium adsorption ratio (SAR[1]). The desired outcomes of the studies were to develop water quality recommendations and management plans related to irrigation of landscapes with recycled waters.

Coastal redwood is the primary plant species of concern. Observed leaf burn and tree death have been associated with irrigation with recycled water, indicating coastal redwood is very sensitive to salinity, sodium, chloride or a combination of all three. For the sustainable irrigation of trees and turf, adequate water infiltration and percolation rates through soil are essential to provide the water needed to maintain acceptable levels of electrical conductivity in the soil water (ECsw) and adequate soil aeration. If these rates are inadequate, the soil will become saturated, increasing runoff. If saturated conditions exist for several weeks, soil aeration will be limited, which can result in inadequate oxygen levels in the soil for trees.

This report uses the information obtained from these studies to recommend water quality requirements and the management practices that may result in healthy redwood trees in landscapes at Shoreline Golf Links in Mountain View, Villages Golf and Country Club in San Jose, and Wilson School in Santa Clara when irrigated with recycled water. To make these recommendations, I also used soil salinity and sodicity levels measured in August 2007 at these three locations.

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[1] SAR = $C_{Na}/\sqrt{((C_{Ca} + C_{Mg})/2)}$ where C represents ion concentration in units of mmol(+)/L and the subscripts are the abbreviations for the chemical elements.

2.0 WATER QUALITY EFFECTS ON SOIL HYDRAULIC PROPERTIES.

Salinity and sodicity indices of water quality. Both salinity and sodicity affect the extent to which soil particles remain together or separate. When soil particles separate, the smaller soil particles can plug the large soil pores through which most of the water flows. This reduces the rate water can move into and through soils.

The higher the salinity of the irrigation water, or of the water in the soil, the more likely it is that soil particles remain together, and the less likely that soil particles will adsorb water and separate. Salts decrease the affinity of soil particles for water, and consequently their tendency to adsorb water and separate. In other words, the greater the salinity, the greater the stability of soil particles. The index for salinity is electrical conductivity of the irrigation water (ECiw), or of the soil water (ECsw).

The higher the sodicity, or sodium content of irrigation water, the higher the SAR of the soil water, SARsw, in the soil irrigated with that water, and the greater the likelihood soil particles will adsorb water and separate. The higher the SARsw, the higher the exchangeable sodium percentage (ESP) of the soil. As a general rule (U.S.D.A Handbook 60, 1954) for $0 < \text{SARsw} < 40$, $\text{ESP} \approx \text{SAR}$. With increasing exchangeable sodium, the affinity of soil particles for water increases and the stability of soil particles decreases. At a given SAR, the higher the ECiw, or ECsw, the greater the soil-particle stability.

Salinity and sodicity guidelines for irrigation water have been developed, and are used to assess the likelihood of adverse effects on water flow (Ayers and Westcot, 1985; Kearney Foundation of Soil Science, 1992). However, considerable judgment is required since no general guidelines apply to all soils (Pratt and Suarez, 1990). This is particularly true where rainfall can reduce the ECsw to near zero at or in close proximity to the soil surface (Oster and Schroer, 1979; Agassi et al., 1981; Quirk, 2001; Suarez et al., 2006).

In recognition of this situation, SCVWD funded the soils studies conducted by Beaudette and Singer (2007), who collected and worked with thirty soils in Santa Clara County. They found that the salinities of the percolating solutions had a larger impact on saturated hydraulic conductivities (Ksat) for a given soil than did the SAR of the percolating solutions.

Generally, Ksat decreased as salinity declined. Beaudette and Singer (2007) summarized the salt concentrations in the soil water at which a 15% reduction Ksat occurred as follows: “Seven of the thirty soils reached this threshold when the 100 mmol(+)/L solution was applied. Seven soils reached the threshold reduction in Ksat at 50 mmol(+)/L, five were affected with the 10 mmol(+)/L solution, eight were affected with the 5 mmol(+)/L solution, and three soils were not affected until deionized water was applied as the percolating solution." Division by 10 of the concentrations in this quote provides a good estimate of the ECsw. Consequently, the corresponding threshold values for ECsw are 10, 5, 1 and 0.5 dS/m.

In regard to the potential impacts of rain on its infiltration, the Ksat of all soils studied by Beaudette and Singer (2007) decreased considerably when the EC of the percolating solution was zero.

Management of recycled water to maintain good rates of infiltration and percolation of water. The EC and SAR of recycled waters are higher than Hetch Hetchy water (Table 1). Salts, particularly sodium salts, are higher for the Palo Alto Regional Water Quality Control Plant (PARWQCB) and South Bay Water Recycling (SBWR) waters than for Hetch Hetchy water (Table 1). Based on the EC of the waters in Table 1, the salt contained in an acre foot of water for Hetch Hetchy, PARWQCP, and South Bay waters is 0.2, 1.2, and 1.1 tons, respectively.

After several irrigations with a given water, the ECsw and SARsw of the surface soil become almost equal to the EC and SAR of the irrigation water. The EC of PARWQCB and SBWR recycled waters (Table 1) are lower than levels (5 < ECsw < 10 dS/m) at which Ksat of 14 of the 30 thirty soils declined more than 15 percent (Beaudette and Singer, 2007). Infiltration of rain will reduce ECsw to levels approaching zero within the upper inch or two of the soil. Thus, rain poses the possibility of further reductions in infiltration rates, as has been documented in several published papers (Oster and Schroer, 1979; Agassi et al., 1981; Quirk, 2001; Suarez et al., 2006). Also, as pointed out by Beaudette and Singer (2007), use of recycled waters with their higher SAR values will add sodium to the soil exchange complex. Although the major finding of their work was that ECsw had a greater influence on Ksat than SAR, where SAR had an effect, Ksat usually decreased with an increase in SAR. The prudent conclusion is that removal of the increased sodium will increase the stability of soil particles and the rate water infiltrates and percolates through soils.

Table 1. Water quality of Hetch Hetchy, Palo Alto Regional Water Quality Control Plant (PARWQCP) and South Bay Water Recycling (SBWR). Hetch Hetchy water is used at Shoreline Links, and SBWR is used at The Villages Golf and Country Club and at Wilson School.

Source of water	pH	EC	SAR	Ca	Mg	Na	K	Cl	HCO_3	SO_4	NO_3
		dS/m		mmolc/L (meq/L)							mg/L
Hetch Hetchy	8.9	0.2	0.78	0.75	0.52	0.62	0.03	0.34	0.95	0.4	nil
PARWQCP	6.6	1.35	5.31	2.30	2.80	8.48	UNK	9.25	1.56	1.01	18.7
SBWR	7.2	1.21	4.01	2.60	2.50	6.40	0.40	5.30	2.90	2.10	9.5

As pointed out by Beaudette and Singer (2007): “One option for managing the sodium and EC is to apply gypsum. Gypsum, along with sufficient leaching water, will help to remove sodium from the soil, and will maintain the EC so that soil structure is preserved.”

A particularly advantageous time of the year to apply gypsum is immediately before the rainy season. Infiltration of rainwater reduces ECsw near the soil surface to near zero. Application of gypsum at a rate of about two tons per acre in the fall before the rainy season begins will maintain ECsw at levels above zero near the soil surface, thereby reducing the effects of rain on infiltration rates. Gypsum in combination with infiltration of rain will remove sodium from the soil surface and leach it to deeper depths. Application of gypsum during the irrigation season will reduce SARsw, thereby decreasing the amount of sodium that needs to be removed. However, it will also increase ECsw. The salinity study conducted by Barnes et al. (2007) shows that an increase in ECsw by all the types of salt used in the study had an equal impact on salinity hazard to redwood trees.

The use of gypsum to mitigate effects of the higher SAR of recycled waters is recommended, but it needs to be used wisely. The amounts need to be limited, and timing needs to taken into consideration. The most critical time is before and during the rainy season, the coolest time of the year. This is the most favorable time to increase ECsw, because salinity effects on plant growth are less pronounced when the weather is cool and humid than when it is warm and dry (Maas and Grattan, 1999).

3.0 WATER QUALITY EFFECTS ON GROWTH OF GRASS AND TREES.

Generally, trees are considerably more sensitive to salinity than are grasses. For fescue and ryegrass, the threshold soil-water salinities, ECsw[2], at which growth is reduced range from 8 to 12 dS/m (Maas and Grattan, 1999). The threshold level for redwood is likely much lower based on the data reported by Barnes et al. (2007). They subjected redwood seedlings, *Sequoia sempervirens* 'Aptos Blue', to different salinity treatments for 16 months (Table 2). The water applied during that time exceeded the amount used by the trees for all salinity treatments by about 40 %. The excess (drainage) water was collected and its EC was measured (Table 2). The average EC of the applied water and drainage water, an estimate of the average ECsw in the rootzone, was 1.2 times the EC of the applied water (Table 2).

Table 2. Electrical conductivities (EC) of the applied water and drainage water for the salinity treatments in the studies conducted by Barnes et al. (2007). The average electrical conductivity of the soil water (ECsw) is the average of the EC of the applied and drainage waters.

Salinity Treatment	Applied water EC	Drainage water EC	Average ECsw
	dS/m		
Control	0.57	0.66	0.62
NaCl	1.05	1.67	1.36
NaCl	3.12	4.52	3.82
NaCl	4.32	5.71	5.02
NaCl	5.72	7.08	6.40
$CaCl_2$	1.06	1.54	1.30
$CaCl_2$	2.95	5.08	4.02
$CaCl_2$	4.52	7.1	5.81
$CaCl_2$	6.12	8.83	7.48
NaCl + $CaCl_2$	1.09	1.61	1.35
NaCl + $CaCl_2$	2.94	4.6	3.77
NaCl + $CaCl_2$	4.59	6.83	5.71
NaCl + $CaCl_2$	6.1	8.4	7.25
Na_2SO4	1.09	1.73	1.41
Na_2SO4	3.1	4.68	3.89
Na_2SO4	4.71	6.08	5.40
Na_2 SO4	6.1	7.37	6.74
Average	3.48	4.91	4.20
Average EC of drainage water/average EC of applied water = 4.91/3.48 = 1.41			

[2] The threshold salinities reported by Maas and Grattan are the electrical conductivity of saturated-paste extracts. I have multiplied them by 2.0 to convert them toECsw.

For all salinity treatments, little or no reduction in trunk diameter occurred when the EC of the applied water was 1.07 dS/m, the average EC of the lowest EC treatments. A reduction in trunk diameter together with moderate leaf burn occurred when the EC of the applied water was 3.03 dS/m, the average EC of the second lowest EC treatments. The corresponding ECsw values are 1.3 dS/m (no reduction in trunk growth) and 3.6 dS/m (reduction in trunk growth with moderate leaf burn). Redwood trees are much more sensitive to salinity than are fescue or ryegrass. Irrigation of redwoods that provides enough water to maintain acceptable values of average ECsw will be more than adequate for grass.

WATSUIT (Oster and Rhoades, 1990) was used to calculate the average ECsw in the rootzone as a function of leaching fraction for the three waters given in Table 1. WATSUIT assumes a 40:30:20:10 water uptake distribution, which is the same distribution used by Ayers and Westcot (1985). Two average ECsw values were calculated: the average ECsw for for the whole rootzone (Fig. 1), and the average ECsw for the upper half of the rootzone (Fig. 2). The ECsw values in both figures are much less than 8 dS/m throughout the range of leaching fractions. Consequently, irrigation of fescue and ryegrass with recycled water does not pose a salinity problem. Redwoods are another matter unless they are irrigated with Hetch Hetchy water. For the two recycled waters, the average ECsw for the whole rootzone (Fig. 1), and for the upper half of the rootzone (Fig. 2), is greater than 1.3 dS/m throughout the range of leaching fractions used to calculate ECsw.

Based on the findings reported by Barnes et al. (2007) for redwoods, an average ECsw greater than about 1.3 dS/m resulted in reduced trunk growth and an average ECsw of 3.6 dS/m resulted in leaf burn for all treatments. To prevent leaf burn, a major quality factor for ornamentals, the target average ECsw in the rootzone needs to be somewhere between 2 and 3 dS/m. For Palo Alto recycled water (Table 1), the most saline recycled water, the leaching fractions required to obtain these average ECsw values range from 0.25 to greater than 0.4 (Fig. 1). If redwood response to ECsw depends more on the average ECsw in the upper portion of the rootzone, than the average ECsw for the whole rootzone, then the corresponding target range of leaching fraction for Palo Alto water ranges from < 0.05 to 0.24 (Fig 2).

Letey and Feng (2007) proposed that plants are probably more responsive to the average ECsw in the upper portion of the rootzone (Fig. 2) than to the average ECsw for the whole rootzone (Fig.1). The salinities in Fig. 2 are considerably lower than those in Fig. 1. A leaching fraction of 0.23 for Palo Alto recycled water would result in an average ECsw of 2 dS/m in the upper portion of the rootzone (Fig. 2). Based on the growth in trunk diameter reported by Barnes et al. (2007), this level of ECsw may result in reduced growth. However, since the salinity treatments did not include one where the average ECsw was 2 dS/m, it is not known whether this average ECsw would cause leaf burn.

Whichever may be the best assumption about how redwoods respond to ECsw in the rootzone, in order to maintain ECsw at levels that do not cause significant damage to redwoods, considerably more water will need to be applied and infiltrated into the soil than what the trees require to meet their needs for evapotranspiration.

Use of recycled water poses a major salinity hazard to redwood trees. Leaching fractions greater than 0.20 to control soil salinity may be difficult or impossible to achieve for soils with low hydraulic conductivities, or for soils where infiltration rates are limiting. Other factors also are important: the need for very good irrigation management over the long run; and the variability of the salt tolerance among individual redwood trees; the erratic nature of rainfall in the area; and in rootzones with high water contents, anoxic conditions that can enhance the impact of soil salinity on leaf burn. Without a demonstrated ability to achieve the needed leaching fractions over the long run while maintaining acceptable levels of leaf burn, I cannot recommend the continual use of recycled waters with salinities greater than 1 dS/m to irrigate redwood trees .

Fig 1. Effect of leaching fraction on average salinity (ECsw) of the soil water in the rootzone calculated using WATSUIT

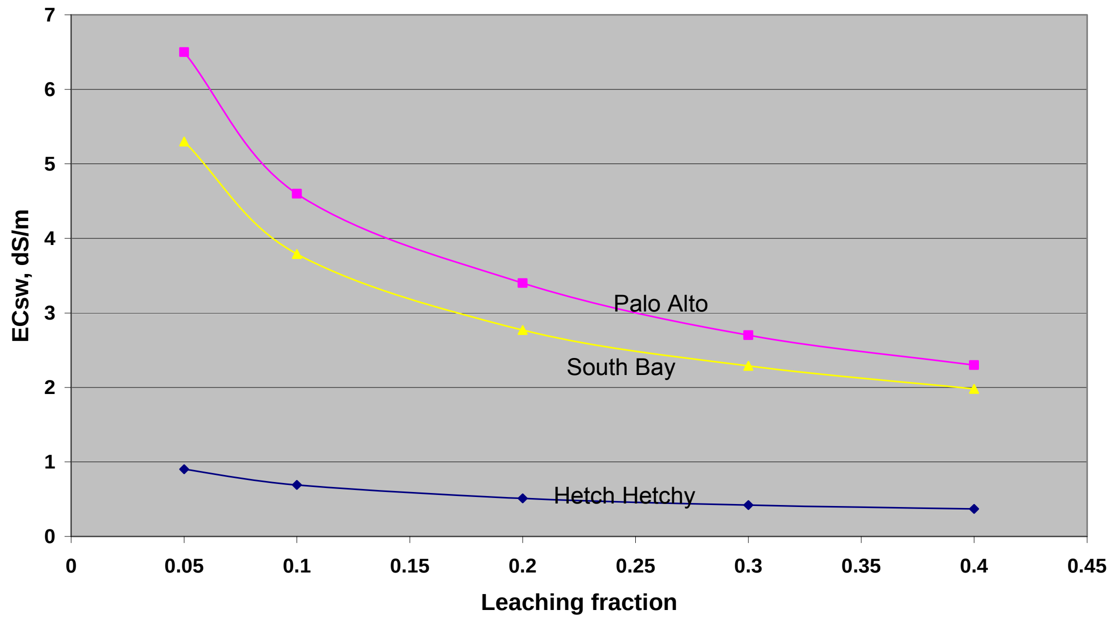
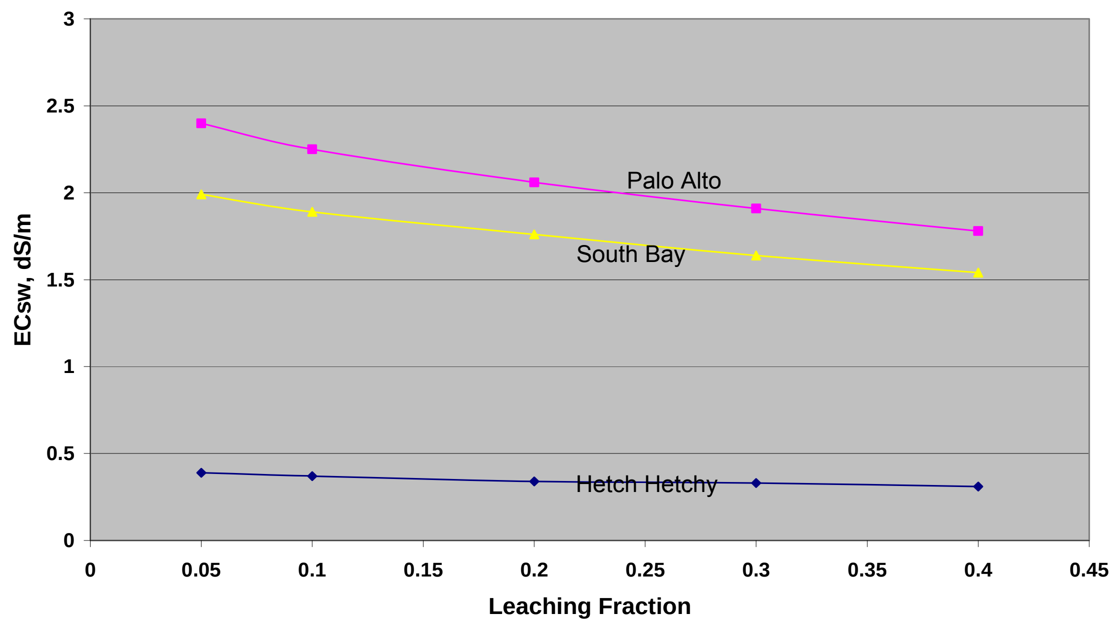


Fig. 2 Effect of leaching fraction on average salinity of the soil water (ECsw) in upper half of rootzone calculated using WATSUIT



4.0 WATER MANAGEMENT

Water requirements for turfgrass and trees can be estimated from reference evapotranspiration (ETo) calculated from measurements at weather stations located throughout California and provided by the California Irrigation Management Information System (CIMIS). The nearest CIMIS station is at Morgan Hill. Table 3 presents monthly values of ETo, which are the averages for the past 10 years. Absent the need to apply extra water to control ECsw by leaching, the water requirement (ETc) for closely clipped, cool season turfgrass equals 0.8 times ETo. The 0.8 is known as the crop coefficient. Where the irrigated landscape includes trees and grass, the crop coefficient for grass will not be affected unless there are several tiers of vegetation i.e. grass and closely planted shrubs, and some trees.

Rainfall is a significant factor that also needs to be accounted for when considering how much irrigation water to apply. The average rainfall during December, January and February exceeds the monthly ETc of closely clipped, well-watered, cool-season grass (Table 3). For the past 10 years, rainfall during December and January exceeded ETc in seven years. Rainfall exceeded ETc in February eight years out of ten. For six years, rainfall from December through February exceeded ETc by at least 7 inches. The rainfall for the individual years was 7, 8, 9, 10, 12 and 18 inches.

Seven inches of excess rain over ETc is sufficient to leach, or remove, about 80% of the salinity in the upper 14 inches of soil; 18 inches would remove about the same percentage in the upper 36 inches of soil (Hoffman, 1986). Consequently, the chance that rainfall will be sufficient to leach the upper 14 inches of soil is fairly high for any given year, and occasionally it will be sufficient to leach salts out of the upper 24 to 36 inches of soil. However, the chances of no leaching by rain are also significant. For December through February, subtracting ETc from rain for each of the other four years resulted in totals ranging from – 4 to 3 inches. Little leaching occurred during these years.

Finally, one needs to consider whether to use a rain-corrected salinity of the water applied during the summer. This is not necessary, since the amount of rain relative to ETc from May through October (Table 3) is about 7%. ETc from May through October totals 27.9 inches, or about 70 % of the total annual ETc. Most of the irrigation will occur during these months, and rain will not provide a significant reduction in ECsw.

Table 3. Average climatic data for the last 10 years at the Morgan Hill CIMIS station. ETo represents reference evapotranspiration of 4- to 7-inch tall cool season grass growing in an open field condition, and ETc represents evapotranspiration from closely-clipped, well-watered, cool-season grass assuming a crop coefficient of 0.8: ETc = 0.8*ETo (http://www.owue.water.ca.gov/docs/wucols00.pdf).

Month	ETo	Rain	ETc	Rain - ETc
	---------------	inch/mo	---------------	
Jan.	1.5	2.7	1.2	1.5
Feb.	1.8	4.3	1.5	2.8
Mar.	3.4	2.1	2.7	-0.6
Apr.	4.6	1.6	3.7	-2.1
May	6.1	0.7	4.9	-4.2
June	7.0	0.1	5.6	-5.5
July	7.0	0.2	5.6	-5.4
Aug.	6.0	0.1	4.8	-4.7
Sept.	5.0	0.1	4.0	-3.9
Oct.	3.7	0.5	3.0	-2.5
Nov.	1.9	0.9	1.5	-0.6
Dec.	1.4	3.3	1.2	2.1
Total	49.5	16.7	39.6	-23.1

Consideration of rain poses a confusing situation when considering how to irrigate redwoods. In general, irrigation needs to be based on ETo as measured on site, or at the Morgan Hill CIMIS station. There is a need to account for rain, particularly during December through February. Consideration of two situations, wet and dry rainy seasons, makes it a bit simpler. The following describes the differences in management of irrigation with recycled water for these two situations. It assumes a leaching fraction of 0.25 is needed to control ECsw, and that all the applied water will infiltrate into the soil.

5. IRRIGATION OPERATIONS

5.1 Wet years. Once two inches of rainfall have occurred in December, or in some years in November, stop regular irrigation with recycled water. Based on weather forecasts and the actual amount of rain at the site, avoid irrigation as much as possible through February. Doing so will minimize the salt applied to the soil, thereby optimizing a reduction in ECsw due to leaching by rain. After February, trees will benefit from the low ECsw in the upper portion of the rootzone. Underirrigation for a period of several months during late winter and early spring would be recommended to decrease the amount of salt added to the soil. However, during the summer, when there is little or no rainfall, the amount of infiltrated irrigation water (AW) needs to be about 1.33 times ETc to achieve a leaching fraction of 0.25 (Table 4).

5.2. Dry years. Applied water needs to be 1.33 times ETc throughout the year to achieve a leaching fraction of 0.25.

5.3. Discussion. The determination of how much water to apply is different for turf than for trees. The amount to apply to turf is based on the entire grassed area. For well-watered trees, the area from which trees obtain most of their water may be somewhat greater than the area shaded by a tree at noon. Multiplication of the shaded area by ETc and conversion to gallons per day yields the amount of water to apply to each tree. Assume a redwood shades a circle with a diameter of 20 feet. The area shaded is 314 ft^2. The daily ETc in June is 0.19 inch (Table 3). Multiplication of the area by 0.19 inch results in a volume of 4.9 ft^3, or 37 gallons, as the daily water requirement in June. If a leaching fraction of 0.25 is desired to control ECsw, then the total amount of water needed daily is 1.33 (Table 4) times 37 gallons, or 49 gallons. Finally, these numbers assume all the applied water infiltrates into the soil; that no runoff occurs.

Table 4: The relationship between leaching fraction and the ratio of applied water, AW, to annual crop evapotranspiration, ETc, and the amounts of AW required for three levels of ETc as a function of leaching fraction. The numbers for AW in the table assume all the applied water infiltrates into the soil and that all the area irrigated receives the same amount of applied water.

		ETc (inch)		
		30	*40*	*50*
Leaching fraction	*AW/ETc*	*AW (inch)*		
0.4	*1.67*	*50*	*67*	*84*
0.3	*1.43*	*43*	*57*	*72*
0.25	*1.33*	*40*	*53*	*66*
0.2	*1.25*	*38*	*50*	*62*
0.15	*1.18*	*35*	*47*	*59*
0.1	*1.11*	*33*	*44*	*56*
0.05	*1.05*	*32*	*42*	*52*

Because these calculations are -- at best -- only estimates, a back-up system based on soil measurements is recommended to assure that irrigation of redwoods is adequate. Several trees should be selected where the irrigation systems are fairly representative of all the irrigated trees. At these trees, a deep (3 ft) and a shallow tensiometer (1 ft), or other calibrated devices that measure soil water content, should be installed at two locations each about 7 feet from the trunk. The tensiometer readings at the 1 ft depth should be used to track the results of irrigation decisions made weekly. If irrigation is adequate, the readings will be less than about 20 kPa, or 20 cbar, several hours after irrigation. The tensiometer readings at the 3 ft depth would be used to track the results of irrigation decisions made monthly. They should be less than about 40. If they trend to values higher than 50, the amount of irrigation needs to be increased. If they trend to values lower than 30, the amount of irrigation could be decreased.

In addition, soil samples should be taken at the same depths and distances from the trees in March and September to determine the electrical conductivities of saturated-paste extracts (ECe). The ECe values need to be converted to ECsw by multiplying by two. Values of ECsw higher than 2.0 dS/m, particularly at a depth of 1 ft. in September, would indicate irrigation has not been adequate. Values in March at 1 ft would be expected to be lower than 2.0 dS/m if rainfall during the previous rainy season was sufficient to leach the soil. If so, then some underirrigation during April and May could be practiced, but with a close eye on the tensiometer readings at the 3 ft depth. They should be not be allowed to reach levels higher than 50. Upon reaching 50 kPa (cbar), full irrigation should begin. Finally, ECsw values in September should be less than 3 dS/m at both depths. If not, then too little water was applied during the summer.

6.0 FIELD OBSERVATIONS, AUGUST, 2007

Existing soil salinities and sodicities were determined on soil samples obtained in Aug. 2007 where recycled water was used or where its use was contemplated. This section deals with how these results compare to what was expected based on the quality of the applied water. It also further addresses how recycled water should be used to irrigate turf and redwood trees.

Soil samples were obtained in August 2007 at The Villages Golf and Country Club course in San Jose and at Wilson School in Santa Clara, where recycled water is used, and at Shoreline Golf Links in Mountain View where predominantly Hetch Hetchy water is used. Soil samples were taken on four fairways about 160 yards from the greens at locations midway between two or three sprinklers. Such a location should be representative of adequate irrigation due to overlapping water-application patterns from the sprinklers. A random number generator was used to select the four fairways. At Wilson School, the four sampling sites were in the irrigated turf about 25 feet from a line of redwood trees along the west side of the property. The first sample was about 195 feet from the south fence, and the distance between sampling sites varied from 100 to 150 feet. The soil was too dry beneath the tree canopies to sample.

Soil samples were obtained with a hand auger from five depth intervals: 2 – 5, 10 – 14, 22 - 26, 34 – 38, and 46 – 50 inches. They were double bagged in plastic zip-lock bags, labeled, and stored in a closed cooler. Field water content was determined at the SCVWD’s Rinconada Laboratory within 48 hours. The remaining samples were sent to Dellavalle Laboratory in Fresno for chemical analysis of saturated-paste extracts. Soil cores of the 2 – 5-inch layer were obtained with a double-cylinder, hammer-driven core sampler for the determination of bulk density and water retentivity at matric potentials of 0, -10, -20 and -40 kPa. These were done in Dr. Laosheng Wu's soil physics laboratories in the Dept. of Env. Sci. at the University of California, Riverside, and the results are in Table 5.

Table 5. Gravimetric water content in the 2 – 5-inch depth interval as a function of soil-water matric potential (ψ), as determined in the laboratories of Dr. L. Wu, at the University of California, Riverside.

Location with Fairway number (FN) for Shoreline and Villages and site number for Wilson School	Bulk density	Gravimetric water content			
		Ψ= 0.0 kPa	Ψ= -10 kPa	Ψ= -20 kPa	Ψ= -40 kPa
	Mg/m^3	%			
Shoreline FN 2	1.37	22.29	19.81	15.32	14.77
Shoreline FN 5	1.37	22.16	22.40	17.86	17.59
Shoreline FN 14	1.38	19.78	18.04	13.65	13.14
Shoreline FN 18	1.54	16.76	17.67	13.63	13.08
Villages FN 2	1.31	20.23	11.92	7.78	7.36
Villages FN 10	1.35	21.71	10.57	6.79	6.10
Villages FN 12	1.49	16.80	10.66	6.83	6.30
Villages FN 14	1.52	15.96	9.83	6.08	5.60
Wilson 1	1.34	21.45	17.74	12.87	12.30
Wilson 2	1.42	17.88	13.92	9.62	8.89
Wilson 3 [Data rejected]	~~0.87~~	~~54.23~~	~~34.42~~	~~29.56~~	~~28.60~~
Wilson 4	1.25	25.24	18.31	14.14	13.31

6.1 Shoreline Links. (Irrigated with Hetch Hetchy water, overlying a clay-capped and sealed land fill) The soil water content in the 2 – 5 inch depth (Table 6) corresponded to estimated soil-water matric potentials less than - 40 kPa at three of the four sites, based on the water retentivity data in Table 5. These low potentials indicate that insufficient water is being applied to meet the water needed by turf for ET plus that needed to control salinity. This finding is consistent with the high ECe, 12.7 dS/m, at the 2 – 5 inch depth, and the decrease in ECe with depth (Table 7).

Table 6. Field water content in the 2 – 5-inch depth interval and corresponding estimated soil-water matric potentials (ψ) for samples obtained on 13 August 2007. ψ was estimated from soil water retentivities (Table 5)

Location with Fairway number (FN) for Shoreline and Villages and site number for Wilson School	Field water content	ψ
	% dry wt.	kPa
Shoreline FN 2	13.0	ψ < -40
Shoreline FN 5	15.1	ψ < -40
Shoreline FN 14	16.9	-20 < ψ < -10?
Shoreline FN 18	11.7	ψ < -40
Villages FN 2	14.6	-10 < ψ < 0
Villages FN 10	14.6	-10 < ψ < 0
Villages FN 12	11.5	ψ ≤ 0
Villages FN 14	15.2	ψ ≤ 0
Wilson 1	12.1	ψ < -40
Wilson 2	12.6	-20 < ψ < -10
Wilson 3	13.3	ND
Wilson 4	18.8	ψ ≈ -10

The 12.7 dS/m in the 2 – 5 inch depth (Table 7), is unusually high considering the electrical conductivity of the Hetch Hetchy water, 0.20 dS/m (Table 1). The same is true for the chloride and sulfate concentrations: for chloride, 48.1 mmolc/L (Table 7) as compared to 0.34 mmolc/L (Table 1); and for sulfate, and 51.9 mmolc/L (Table 7) as compared to 0.40 mmolc/L (Table 1).

There was considerable variability in ECe (Appendix B) among the four sampling sites for the 2 – 5 inch depth. The individual values were: 2.3, 7.2, 17.5 and 23.9 dS/m. For the 46 - 50 inch depth the variability was smaller: the individual values were 6.1, 7.9, and 8.4 dS/m. Note that only three sites were sampled to a depth of 50 in. A rock precluded sampling deeper than about 26 inches at S2. The relative variabilities for the individual chemical elements were similar to the variability for ECe.

The decrease in ECe with depth is a normal distribution **if** a shallow water table is present. However, if a water table had been present at depths less than 50 inches, it would have been evident: the soil at the 46-50 inch depth would have

Table 7. Soil chemistry of saturated-paste extracts. Except as noted with an asterisk, values are averages of four samples; values with an asterisk are averages of three samples. Analyses run by Dellavalle Laboratory, Fresno CA. SP and FW represent saturated-paste and field water content; ECe represents electrical conductivity of the saturated-paste extract, and SAR represents sodium adsorption ratio.

location	Depth interval	SP	FW	pH	ECe	SAR	Cl	SO_4	NO_3
	inches	%			dS/m		mmolc/L		mg/L
Shoreline	2 - 5	51.3	14.2	7.8	12.7	8.5	48.1	51.9	17.1
	10 - 14	46.5	15.9	8.0	7.7	6.0	14.4	38.4	16.7
	22 – 26	44.0	24.3	7.9	6.4	6.4	13.6	25.1	11.7
	34 – 38 *	52.7	15.4	7.9	4.9	4.3	6.2	13.4	7.4
	46 – 50 *	48.7	25.8	7.8	7.5	4.5	8.2	19.0	72.8
Villages	2 - 5	33.8	14.0	7.4	4.4	5.6	12.6	17.1	3.8
	10 - 14	38.8	11.0	7.2	7.5	5.7	33.3	34.3	10.5
	22 – 26	27.3	11.2	7.4	4.3	5.5	16.5	23.2	9.2
	34 – 38	28.3	12.4	7.3	4.7	5.8	19.8	23.0	9.8
	46 - 50	29.0	13.0	7.3	3.9	8.4	16.1	19.0	4.6
Wilson	2 - 5	36.0	14.2	7.5	3.4	5.1	29.9	8.7	2.7
	10 - 14	45.3	8.6	7.5	5.1	6.6	45.0	9.3	27.2
	22 – 26	33.6	7.4	7.7	2.3	6.6	18.5	4.4	11.7
	34 – 38	33.3	7.1	7.7	1.7	3.9	11.2	3.9	8.3
	46 - 50	31.8	6.8	7.7	2.5	2.9	20.4	6.0	1.8

been very wet, and water would have begun to fill the lower portion of the sample hole. We did not encounter either. However, this does not preclude the possibility that there are times during the year, particularly during the rainy season, when the water table could be shallow. If so, then during the spring and summer the water table could drop because of slow downward percolation – mostly precluded because of a clay cap over the underlying landfill – and water use by the turf, trees and shrubs.

Another possibility is that ECe of 12.7 dS/m (Table 7) in the 2 – 5-inch depth is a consequence of underirrigation for several years with a consequent accumulation in the soil of the salts applied in the irrigation water. This would require the application of a large amount of irrigation water that has an EC of 0.20 dS/m. Based on the ECe of the 2 – 5-inch depth and the EC of Hetch Hetchy water, 0.2 dS/m (Table 1) it would take 25 cubic feet of water per square foot of soil, i.e. 25

feet of water, to apply the salt contained in this 3 inch depth interval. Assuming 2 feet of water are applied per year, it would take 12 years, to achieve the ECe measured in this small portion of the soil profile. Similar times were obtained using the chloride and sulfate concentrations (Tables 7).

> The following summarizes the calculations of the amount of salt, 0.097 lbs, in the 2-5 inch depth with an area of a square foot. 1. The ECe of 12.7 dS/m (Table 3) is converted to ppm using a factor of 640. The result is 8100 ppm. 2. A cubic foot of soil is assumed to have a mass of 93 lb (bulk density of 1.5 Mg/m^3). 3. At a soil water content of 51 % (=saturation percent, SP), there would be 12 lbs of water in a saturated paste made using all the soil in 2-5 inch depth with an area of a square foot. 4. Using a salt concentration of 8100 ppm, the amount of salt in the water is 0.097 lbs.
>
> The following summarizes the calculation of the mass of salt in a cubic foot of water. The EC of the Hetch Hetchy water, 0.2 dS/m, is converted to ppm using a factor of 640. The result is 128 ppm. 2. A cubic foot of water has a mass of 62 lb. 3. The mass of salt in a cubic foot of Hetch Hetchy water is 0.0038 lbs.

How representative were the four sites of the rest of the golf course? Based on the results of the EM survey of the entire course, conducted under the leadership of Dr. F. Cassel in April 2005, ECe's of less than or equal to 6 dS/m in the upper two feet of soil occurred in 30 – 50% of the areas in all fairways, with ECe's of greater than 6 dS/m in 5 – 15% of the area. Had the survey been done during August, the values would likely have been higher. The ECe values for the 2 – 5 inch depth obtained in August (Appendix B) at two of the locations are somewhat higher than expected based on the EM survey in April of 2005, but could not be considered to be excessively high.

It is reasonable to conclude the high salinities are not just the consequences of irrigation with Hetch Hetchy water. Other sources of salt that need to be considered include: irrigation with more saline water; the native salt in the soil, and upward movement of salt from deeper depths.

Whatever the explanation for the high ECe values, they must have occurred because the combination of existing water management and drainage precluded the ability to achieve some leaching. The average ECe values in the upper two feet of soil (Table 7) are sufficiently high to reduce the growth rate of moderately-tolerant, cool-season grass species such as fescues and ryegrass. The threshold ECe values for these grass species range from 4 to 6 dS/m (Maas and Grattan, 1999). Application and infiltration of more water than used by the turf on the fairways is urgently needed to reduce the soil salinity. However, doing so assumes the excess applied water will be able to move downward to depths below the rootzone. This may not be possible since the underlying clay layer seals and prevents downward movement of water into the land fill.

Since water management and drainage are limiting, any increase in the EC of the irrigation water will increase soil salinity. An increase in EC will require an increase in the amount of applied water that needs to infiltrate into the soil to maintain acceptable ECe levels. In turn, this will increase the soil water content and increase the amount of water that moves downward through the rootzone. This could be done with an irrigation system that does not apply water uniformly. However, the more nonuniform the application, the greater the amount of water required and the greater the need for subsurface drainage. However, the installation and maintenance of a drainage system that meets the needs for leaching and control of the water table depth could be difficult, considering that the underlying strata is a clay-capped landfill. Because of the hilly topography of the golf course, it is likely the depth to the clay layer is not uniform. The installation of additional drainage systems would need to take both the depth to the clay layer and the hilly topography into account to optimize the location of the drains. Drains need to be located below the water table in order to work. In addition, maintenance of the drainage system will need to contend with continual settling of the material in the landfill and overlying soil, which could result in breaks and blockage of the subsurface drain lines.

In summary: More irrigation water must be applied, and must infiltrate, than what is currently the case. A drainage system is required to remove the excess water needed to control soil salinity. Irrigation scheduling should adjust for climate so that more water is applied than used by turf. The amount of applied water should also be adjusted for irrigation uniformity, assuming it is not 100 % uniform. This should result in a large reduction in ECe in the upper foot of soil (Table 7), and gypsum may need to be applied to maintain infiltration rates, and to reduce areas in the fairways that become too wet.

Based on data reported by Beaudette and Singer (2007), the hydraulic conductivity of two of ten of the Shoreline soils decreased more than 15% when ECsw was less than about 5 dS/m (ECe of 2.5 dS/m), and for another two, a 15 % decrease occurred at an ECsw of 1 dS/m (ECe of 0.5 dS/m). Areas containing these soils will benefit from gypsum provided drainage is adequate.

Conclusion: Changing to PARWQCP recycled water, or a blend of recycled and Hetch Hetchy water, would be a mistake under existing conditions. Further, it is problematic that these conditions can be changed sufficiently to make the change possible in the future.

6.2 Villages Golf Course (Irrigated with South Bay recycled water). The soil water contents in the 2 – 5 inch depth (Table 6) correspond to estimated ψ values ranging from 0 to -10 kPa. A ψ of 0 would occur if the soil was saturated with water, and a somewhat lower water content occurs at a ψ of -10 kPa. These matric potentials indicate that sufficient irrigation water is being applied to provide the water needed by the grass. Based on the ECe and Cl concentrations of the 2 – 5 and 10 – 14-inch depths (Table 7), more water was applied than used by the grass. The excess water results in leaching, which controls the level of ECe in the rootzone. However the amount of excess water, or leaching fraction, is small.

6.2.1 Leaching fraction (LF). LF is the amount of water that moves downward, within and below the rootzone, divided by the amount of applied water. One can estimate LF by calculating ECsw and dividing it into the EC of the irrigation water (Table 1). The calculation involves two steps. The following shows the LF calculations for the 2 – 5 inch depth using the data given in Table 6.

1. First, ECsw is calculated:

ECsw = ECe(SP/FW) = 4.4(33.8/14) = 10.6 dS/m,

where SP is the water content of a saturated soil paste, and FW is the soil water content when the samples were obtained (Table 6).

2. Then the LF is calculated:

LF = ECiw/ECsw = 1.2/10.6 = 0.11.

> Where soil salinity within and below the rootzone of an irrigated soil does not change with time, the mass of salt added per unit of applied irrigation water must equal the mass of salt that leaves the rootzone in the drainage water. The mass of salt in a unit of water (V) equals the salt concentration [C] in the water times V. In other words, where soil salinity within the rootzone does not change with time, the mass of salt applied in the irrigation water, CiwViw, equals the mass of salt in the drainage water, CdwVdw, where the subscripts iw represents irrigation water and dw represents drainage water:
>
> *(Ciw)(Viw) = (Cdw)(Vdw),* *Eq.1*
>
> *or*
>
> *Vdw/Viw = Ciw/Cdw.* *Eq.2*
>
> *Leaching fraction (LF) is*
>
> *LF = Vdw/Viw...* *Eq. 3*
>
> *According to equation 2,*
>
> *LF = Vdw/Viw = Ciw/Cdw.* *Eq.4*
>
> *EC is proportional to C where the proportionality between EC and C is approximately independent of C. Consequenlty*
>
> *LF = ECiw/ECdw* *Eq.5*
>
> .
>
> *(Hoffman and Durnford, 1999).*

The chloride concentrations in the saturated-paste extract can also be used to calculate LF, following the same two-step calculation, where ECe is replaced by chloride concentration (Table 6). The result is a LF of 0.17. Since chemical reactions that involve dissolution of calcite affect ECe, but not chloride concentration, the LF obtained using chloride concentration likely is the best estimate.

The LF for the 10 – 14inch depth can be calculated with the same procedure. LF is 0.04 using ECe, and 0.05 using chloride concentration. This close agreement in LF, as compared to the results obtained from the 2 – 5 inch depth, results from the higher ECe in the 10 -14 inch depth, 7.7 dS/m, and consequently a lower relative error in calculating ECsw due to calcite dissolution.

A LF of 0.05 is lower than expected for the well watered situation at Villages. A higher leaching fraction could be expected for two reasons: 1. the soil water contents were high; the soil was wet enough for water to move downward in response to gravity, and 2. At the CIMIS station at Morgan Hill, the 10-year average rainfall between December 1 through February. 28 exceeds 0.8*ETo by a total of 6.4 inches (Table 2). 0.8*ETo is the estimate of evapotranspiration by turf. This would be sufficient to lower the ECe present on Dec. 1 by about 80 % (Hoffman, 1986) in the 0 – 14-inch depth at the end of February.

However, the rainfall that occurred between December 1 2006 and March 31, 2007 was 2 inches less than ETc for the same time period. Consequently, there was little or no leaching due to rain during the 12 months prior to Aug. 2007, when the soil samples were obtained. And the amount of salt in the 0 – 14 inch depth is consistent with that applied during one year of irrigation with SBWR water. Based on the average ECe of the 2 – 5- and 10 – 14inch depths, it would take about 3 feet of South Bay water to apply the salt contained in the 0 – 14 inch depth. This amount of water is somewhat less than the ETc for one year, 39.6 inch, or 3.3 ft (Table 2). Considering the small amount of rain during the preceding year before the soil samples were obtained, it is likely that more than 3.3 feet of SBWR water was applied.

The chloride concentrations for the depths below 10 – 14 inches also provide valuable information about leaching fractions. Downward movement of water due to leaching occurs slowly at depths below 2 feet. Consequently, the deeper one samples an irrigated soil, the further back in time one needs to consider when interpreting the results. Irrigation with South Bay water began in 2001 and continued until early 2004. Rainfall between Dec. 1 and Nov. 30 for the 2001-02 and 2002-03 seasons was 1.4 and 23.1 inches. Then use of South Bay water began again in July 2005 and continued without interruption until the end of July, 2007. The course was irrigated with potable water for August, September and October, 2007. Rainfall between Dec. 1 and Nov. 30 for the 2005-06 and 2006-07 seasons was 23.3 and 9.8 inches. The average rainfall during these years was 18 inches, or 1.5 feet. Because this amount of rainfall provides a significant portion of water to meet the needs of the crop, including leaching, one needs to use a rain-corrected average chloride concentration of the applied water. To make this calculation, the EC of rain is assumed to equal zero. Assuming that the total applied water is about 4.0 feet, of which 1.5 feet are rain, the rain-corrected chloride concentration of the applied water is about 3.3 mmolc/L. The chloride concentrations in the 20 – 24, 36 – 40, and 46 – 50-inch depths range from 16.1 to 19.8 mmolc/L (Table 7). Using the calculation procedure described above, the resulting leaching fractions range from 0.07 to 0.09, using 3.3 mmolc/L as the average chloride concentration in the applied water.

Conclusion: leaching fractions through and below the rootzone range from 0.05 to 0.10 under existing water management practices at Villages.

6.2.2 Leaching requirement. Is this range of leaching fractions adequate for moderately salt-tolerant turf grasses such as fescue or ryegrass, or redwood trees which are sensitive to salinity? The answers to these questions require consideration of changes in soil salinity that can occur during the year. Rain is usually sufficient in December through February to reduce the salinity in the upper foot of soil because rainfall exceeds ETc as is evident in Table 3. The soil salinity would then be expected to increase during March through about May, because the salt in the irrigation water is being added to the soil.

I chose to answer these questions based on the calculated steady-state salinities using the program WATSUIT (Oster and Rhoades, 1990). Doing so provides a worst-case scenario that I consider appropriate because steady state conditions in the upper foot or two of soil should be established by July. The consequences of adding gypsum were also taken into consideration, as were two leaching fractions, 0.1 and 0.3, and the possibility of blending South Bay water with potable water. To account for gypsum application, 13 mmolc/L were added to the Ca and SO4 concentrations in the SBWR water. This addition corresponds to an application of 6 tons/acre of gypsum dissolved in 4 acre feet of water. The average ECsw and SARsw for the whole rootzone and for the upper half of the rootzone are given in Table 8.

For leaching fractions of 0.10 and 0.30, the calculated ECsw values for South Bay (SB) recycled water (Table 8) pose no salinity hazard for turf. However, they pose serious salinity hazards for coastal redwood (Barnes et al., 2007) based on the average ECsw for the whole rootzone, and a potential hazard based on the average ECsw for the upper half of the rootzone. The existing leaching fractions at the time the soils were sampled were adequate for turf but not redwood trees.

Table 8. Soil-water electrical conductivity (ECsw) and sodium adsorption ratio (SARsw) for South Bay (SB) and a 50:50 blend of South Bay (SB) and Evergreen potable (EG) waters for two leaching fractions, with and without gypsum. Values for the average ECsw and SARsw are for two cases: whole rootzone and upper half of the rootzone. The impact of gypsum on the composition of the irrigation water was simulated by adding 13 mmolc/L to Ca and SO4 concentrations of the irrigation water. WATSUIT was used to calculate ECsw and SARsw.

A. Leaching fraction of 0.10

Water/amendment	ECsw, dS/m		SARsw	
	whole rootzone	upper half of rootzone	. whole rootzone	upper half of rootzone
SB	3.8	1.9	8.3	5.4
SB + 6 ton/acre gypsum	5.2	3.1	5.1	2.9
50:50; SB:EG	2.6	1.3	6.0	3.9
50:50; SB:EG + 6 ton/acre gypsum	4.1	2.6	3.5	1.9

B. Leaching fraction of 0.3

Water/amendment	ECsw, dS/m		SARsw	
	whole rootzone	upper half of Rootzone	Whole rootzone	upper half of Rootzone
SB	2.3	1.6	5.8	4.8
SB + 6 ton/acre gypsum	3.7	2.7	3.2	2.6
50:50; SB:EG	1.6	1.2	4.2	3.6
50:50; SB:EG + 6 ton/acre gypsum	3.0	2.3	2.2	1.8

6.2.2.1 Turf: In the fairways, leaching fractions through and below the rootzone range from 0.05 to 0.10 under existing water management practices at Villages.

For moderately salt-tolerant, cool-season turf grass, such as fescue and ryegrass, none of the ECsw values in Table 8 pose a hazard. For a salinity hazard to be considered possible, the threshold levels in ECsw would need to range from 8 to 12 dS/m. This assumes that the threshold salinities for these crops reported in ECe (Maas and Grattan, 1999) result in ECsw when multiplied by two. Consequently, a leaching fraction of 0.1 would be sufficient for South Bay recycled water. This conclusion applies also to the application of gypsum to maintain or improve the rate water infiltrates or flows through soil.

6.2.2.2 Redwood trees: The threshold ECsw above which growth would be reduced is about 1.2 dS/m (Barnes et al., 2007), with major reductions in growth and moderate leaf burn expected to occur at ECsw greater than 3.6 dS/m.

Based on the average ECsw for the whole rootzone (Table 8), where a 50:50 blend of South Bay and Evergreen waters, with an average EC of 0.8 dS/m, is used for irrigation, the targeted leaching fraction to prevent moderate leaf burn (EC < 3.6 dS/m) would be less than 0.10 without using gypsum amendment and somewhat less than 0.3 if gypsum amendment is used. If only South Bay water is used, than the target leaching fraction would need to be somewhat greater than 0.1 without using gypsum amendment and greater than 0.3 if gypsum is used.

If the average ECsw in the upper half of the rootzone better relates to the response of redwood to soil salinity, then these leaching fraction targets would be lower, with the highest targeted value being 0.10. However, this criterion for assessing targeted leaching requirements is still under study. It is included in this report to encourage future research to assess its validity, but it will not be used for making recommendations.

Water management on a golf course must deal with several constraints. Irrigation cannot occur when there are players on all the fairways. Playing on wet grass is not a preferred condition. Play cannot occur in areas where the soil is too wet to support the weight of golfers. There usually are areas where soil physical properties, such as low infiltration rates or low hydraulic conductivities, are limiting. They sometimes cannot be overcome by good irrigation and amendment practices. Consequently a recommendation to increase the amount of applied water at Villages to increase the leaching fraction in areas where redwood trees obtain water may not be possible to achieve with the existing irrigation system.

Conclusion. Blending recycled water with another source of water to reduce the EC of the applied water to 1.0 dS/m is recommended provided a targeted leaching fraction of at least 0.1 can be achieved during the summer in areas beneath the tree canopy. If only recycled water is used then the targeted leaching fraction needs to exceed 0.1, and could be as high as 0.3. Consequently the use of recycled water with an EC greater than 1.0 dS/m is not recommended.

6.2.3 Soil hydraulic conductivity, or soil permeability. Based on Beaudette and Singer (2007), the hydraulic conductivity of one of five of the Villages soil samples decreased more than 15% when the ECsw was less than about 5 dS/m; the same occurred for one soil at a salinity of 1 dS/m; two soils at a salinity of 0.5 dS/m, and one soil at a salinity of zero.

Consequently, reduction in hydraulic conductivities due to low ECsw is a possibility that requires consideration, and application of gypsum would be the recommended practice. Low ECsw during the rainy season poses the greatest likelihood of reduced rates of infiltration and water movement through soils (Oster and Schroer, 1979; Agassi et al., 1981; Quirk, 2001; Suarez, 2006).

If gypsum amendment is considered necessary, its use needs to be minimized because it increases the salinity hazard for redwood trees. All sources of salt were equally effective in causing leaf burn and in reducing growth of redwood. This was one of the major findings of the plant studies done at the University of California at Davis (UCD). Gypsum needs to be used sparingly, and attention needs to be paid to applying gypsum when it will be most effective. If gypsum amendment is necessary, a rate of about 2 tons per acre should be considered and it should be applied in late November or early December

6.3 Wilson School. The soil water contents in the 2 – 5-inch depth (Table 7) correspond to estimated ψ ranging from 0 to -40 kPa, which indicate that sufficient irrigation water may have been applied to provide the water needed by the turf. However, the water contents at depths below 10 inches are about one-half that in the 2 – 5-inch depth (Table 7). This decrease in water content with depth was not due to a remarkable change in soil texture with depth [see Appendix A]. Consequently, the higher water contents in the 2 – 5-inch depth likely resulted from a recent irrigation. The soil water content distribution with depth indicates that the turf is being underirrigated.

6.3.1. Leaching Fraction. The water, SBWR (Table 1), used at Wilson School has an ECiw of 1.2 dS/m with a chloride concentration of 5.3 mmolc/L. Using an ECiw of 1.2 dS/m and the method described in Section 6.2.1, the LF in the 2 – 5- and 10 – 14-inch depths ranged from 0.04 to 0.14. Using the chloride concentration, the corresponding range in LF was 0.04 to 0.07. At deeper depths LF ranged from 0.04 to 0.09 using rain-corrected ECiw (0.8 dS/m) and chloride concentration (3.5 mmolc/L). These low values for LF coupled with the low soil water contents below 10 inches (Table 7) indicate the grass at Wilson School is being underirrigated.

Underirrigation has some advantages in terms of salinity management. The less irrigation water applied, the slower the buildup of soil salinity. Also, the average salinity of the applied water, corrected for rain, is lower, since the relative contribution of rainfall to the total water applied increases as the amount of applied irrigation water decreases.

6.3.2 Turf: Since the grass is relatively tolerant of salinity and water stress, underirrigation doesn't pose a problem for using the grassed area for soccer, softball and etc.

6.3.3 Redwood trees: There doesn't appear to be any irrigation water applied beneath the canopy of the trees at Wilson School. Because it is very difficult to obtain soil samples with a hand auger in soils that are dry and hard, we were unable to sample beneath the trees. We sampled as close to the trees as possible.

All the ECe levels (Table 7) pose a hazard to Redwood trees, which is clearly evident when ECe is converted to ECsw. If irrigation water is not being applied beneath the tree canopy, the trees likely are also subjected to moderate water stress. The only source of water for the trees during the summer is the water applied to the grass. For this source to be significant, the lateral extension of the root system from the trunk would need to be more than 8 to 15 feet. It seems unlikely that the trees can survive the current situation, assuming application of South Bay water will continue to be used. If so, a separate irrigation system should be installed to irrigate the Redwood trees. That assumes it is essential that the trees survive at Wilson school.

A separate irrigation system is needed even if South Bay water is blended with potable water on a 50:50 basis. If the EC of the blended water is 0.9 dS/m, sufficient water needs to be applied during the summer to result in a LF of 0.10. A bubbler system (2 to 4 bubblers per tree) in combination with low border dikes to confine the water to 25 to 50 % of the area beneath the trees, would permit deep watering once or twice a week. Irrigation would need to start in about April and continue until more than two inches of rain occurs (~ Dec). During the irrigation season, the total amount of applied water per month should equal, or somewhat exceed, 1.1*ETo, calculated for an area equal to that covered by the canopy.

Blending potable water with South Bay water may not be legal considering the need to protect drinking water quality at the School. If potable (ECw ≈ 0.6) is the only alternative source of water to irrigate the trees, then the recommended LF would be 0.1 to maintain average rootzone ECsw levels at less than 3 dS/m. In this case, the separate irrigation system for the trees and water management practices described in the previous paragraph would still be recommended.

Consideration should be given to installing instruments to measure the soil water content to a depth of about 5 – 7 feet beneath the tree canopy. It is important to apply enough water to control both salinity and water stress without applying too much water. Too much water could result in poor soil aeration, and anoxic conditions for the roots. Anoxic conditions have been known to reduce the ability of some species of trees to tolerate salinity.

<u>Conclusion:</u> At Wilson School, the South Bay water can continue to be used to irrigate turf using existing water management techniques. However, if the coastal redwood trees along the property boundary are to survive, a separate irrigation system for the trees needs to be installed and the salinity of the applied water should not exceed about 1.0 dS/m. For the redwood irrigation system, blending recycled water with another source of water to reduce the EC of the applied water to 1.0 dS/m is recommended <u>provided</u> a targeted leaching fraction of at least 0.1 can be achieved during the summer in areas beneath the tree canopy. If only recycled water is used then the targeted leaching fraction needs to exceed

0.1, and could be as high as 0.3. Consequently the use of recycled water with an EC greater than 1.0 dS/m is not recommended.

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Appendix A. Field notes

Wilson School. Sampling date 8/13/2007; Erica and Bob

Sampled along S to N tree line

38 redwood trees along this line

Sample sites located along a line parallel to these trees, about 30 feet from the trees.

Grass was growing at all the sites.

Site 1 (W1); Between tree 7 and 8, 19 ft from tree line, 195 ft from S. Fence
Site 2 (W2): Between trees 14 – 16, off the end of the street W of the tree line, 27 feet from the tree line, 98 ft N of W1.
Site 3 (W3): Between trees 21 – 24, 21 ft from the tree line, 152 ft N of W2.
Site 4 (W4): Between trees 28 – 32, 29 ft from the tree line, 153 ft N of W3.

Leaf burn of the redwood trees along the S-N tree line may be related to distance from tree to lawn: with burn increasing as the distance increases. Tree line is not watered, or if it is, the amount of water applied is insufficient for grass to grow. The width of the bare area (tree line to where grass is growing) ranges from about 8 – 15 feet.

Soil texture:

Site number	0 – 6 inches	Below 2 ft
W1	Clay loam	Loam to Sandy Loam
W2	Sandy Clay Loam	Loam to Sandy Loam
W3	Sandy Clay Loam	Loam to Sandy Loam
W4	Sandy Clay Loam	Loam to Sandy Loam

Sampling depths:

Marked (inches)	Actual (inches)
2 - 5	2 – 5
10 - 14	10- 14
	22 – 26
	37 – 41
	50 – 52

Shoreline golf course: sampling date 8/13 (Fairways 2 and 5) in the evening (Erica and Bob) and 8/15 (Fairways 14 and 18) early morning (Bob).

Shoreline #2 (S2). Fairway 2; 150 foot marker at edge of poor area that was midway between two sprinklers. Center of fairway. Had to wait for two golfers to pass.

Shoreline #5 (S5) Fairway 5; 150 foot marker – side slope, left of center, midway between two sprinklers.

Shoreline #14 (S14) Fairway 14; 175 foot marker, left of center, midway between three sprinklers. Sampled early morning

Shoreline #18 (S18) Fairway 18; 175 foot marker, center, midway between three sprinklers.

Site number	0 – 6 inches	6 – 48 inches
S2	Clay loam	Clay, Clay Loam, Silty Clay Loam
S5	Loam	Couldn't sample below about 30 inches
S14	Loam	
S18	Sandy Clay Loam	Variable textures, including clay

Villages golf course: sampling date 8/14 (Fairways 2 and 10) between about 5 and 6 pm and (Erica), and (Fairways 12 and 14) between 6:30 and 8:15 (Erica and Bob). As with Shoreline, sampling locations were midway between two or three sprinklers.

Villages #2 (V2). Fairway 2; 225 foot marker west of center line about 30 feet East of marker. Had to wait for two lady golfers. Redwood tree with leaf burn along left side about 200 feet from white tees.

Villages #10 (V10). Fairway 10;175 foot marker right center between 2 sprinklers. Had to wait for two lady golfers.

Village #12 (V12) Fairway 12; 175 foot marker.

Village #12 (V12) Fairway 12; 175 foot marker, middle of fairway.

Site number	0 – 6 inches	6 – 48 inches
V2	Sandy Clay Loam to Loam (Rocky)	Same texture range as 0 – 6 inches and Rocky
V10	Loam	Same texture range as 0 – 6 inches and Rocky
V12	Sandy Clay Loam (rocky)	Same texture range as 0 – 6 inches and rocky, but not as much as V10
S14	Loam	Same texture range as 0 – 6 inches and rocky, but not as much as V10

Appendix B.
Dellavalle Lab. Data (Excel file)

Determining the Tolerance of Coast Redwood,

Sequoia sempervirens 'Aptos Blue'

to Sodium and Chloride

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August 2007

Introduction

Limited water resources in a state experiencing rapid population growth has stimulated the conservation of potable water and the use of recycled water for landscape irrigation in many locations throughout California (Wu *et al.*, 2000-2001). Sodium and chloride, two of the main constituents in the treated recycled water, have been suspected of causing the decline of redwood trees in the California South Bay Area where this water is used to irrigate public landscapes such as parks and golf courses. Symptoms noted on some redwoods irrigated with recycled water include leaf necrosis and in severe cases, branch and whole tree death.

South Bay Water Recycling serves the cities of Milpitas, Santa Clara and San Jose delivering an average of 15 million gallons of recycled water per day during the summer months (South Bay Water Recycling: About the System). The electrical conductivity (EC) of this water typically ranges from 1.0-1.5 dS/m (South Bay Water Recycling: Water Quality). In most years, sodium (Na) and chloride (Cl) are on average the ions in largest concentration in this water.

The objectives of this study are to determine the level of tolerance of Coast Redwood to these two ions by quantifying growth retardation, leaf ion accumulation and by recording the development of leaf burn symptoms in response to a set of salinity treatments composed of several salt concentrations and compositions.

Materials and Methods

Greenhouse Setup

Sequoia sempervirens ‘Aptos Blue’ saplings in #2 containers (~8 L) were arranged at 1 m alternate spacing in greenhouse 181 in the UC Davis Environmental

Horticulture Complex (Figures 1, 2). Trees were supplied by Van's Nursery in Modesto, California. Containers were approximately 21 cm tall and 21 cm in top diameter, tapering to approximately 18.5 cm at the base. *Sequoia sempervirens* 'Aptos Blue' has been reported as salt sensitive (Wu and Dodge, 2005) to a greater extent than the 'Los Altos' cultivar (Wu and Guo, 2006) and is a popular commercial variety (Wu and Guo, 2006). At the time this experiment was designed, *S. sempervirens* 'Aptos Blue' and 'Los Altos' appeared to be the only two cultivars previously studied with relation to salt sensitivity. Trees were divided into two blocks to control for gradients of sunlight, temperature and humidity across the house. Six trees replicated each of 16 salt treatments. Each block contained three randomly placed replicates for each treatment. The control treatment consisted of nine total trees; five in block 1 and four in block 2. Greenhouse day low and high temperature set points were 20.6 and 23.9 °C and night low and high temperature set points were 12.8 and 16.7 °C, respectively. No artificial lighting was supplied to the plants. The potting mix contained humus : sand in a 4 : 1 volumetric ratio, 6.0 kg/m^3 dolomite, 0.6 kg/m^3 calcium nitrate, 1.2 kg/m^3 ferrous sulfate heptahydrate, 3.0 kg/m^3 nitroform, 2.4 kg/m^3 treble super phosphate and 1.2 kg/m^3 oyster shell lime.

All treatments received a modified Hoagland's fertilizer "Solution 2" at an electrical conductivity (EC) of 0.5 dS/m (Table 1) (Hoagland and Arnon, 1950). This one-quarter strength Hoagland's solution served as the control irrigation treatment. Four salinity types were applied: sodium chloride (NaCl), calcium chloride ($CaCl_2$), an equimolar combination of sodium chloride and calcium chloride (NaCl + $CaCl_2$) and sodium sulfate (Na_2SO_4) (Table 2). Sodium chloride was included to test the effects of these two ions together, as they are the two constituents suspected of damaging coast redwood specimens in the field. Sodium sulfate was used to isolate sodium symptoms and calcium chloride served to isolate chloride symptoms. An equimolar combination of NaCl and $CaCl_2$ provided a treatment simulating environmental conditions, where more than one cation would be present in quantity in the irrigation water and/or soil (Oster, pers. comm.). Each salt type was added to the base Hoagland's solution to attain 16 treatments with conductivities of 1.0, 2.0, 3.0 and 4.0 dS/m. Treatments were initialized on 10/15/05. The dihydrate form of $CaCl_2$ and the anhydrous form of Na_2SO_4 were used for all treatments requiring these salts. Certified ACS-grade chemicals (meeting American Chemical Society purity standards) were selected for all ingredients except the iron chelate solution (Monterey Iron-All 5%, Monterey AgResources, Fresno, CA).

Three Netafim® Woodpecker pressure compensating emitters (Netafim Irrigation, Fresno, CA, rated 4 L/h) at each pot produced an average total flow rate of 12.8 L/h (standard error = 0.08, n = 9). Multiple emitters at each pot allowed for uniform saturation of the container medium, permitted daily irrigation of 17 stations in a timely period (± 1 h) and supplied sufficient flow rate for proper operation of the chemical injectors. Eighteen Dosatron® DI-16 injectors (Dosatron – North and Central America, Clearwater, FL) supplied the treatment solutions at the appropriate EC (Figure 3). The concentrated stock Hoagland's solution recipe was divided into two parts. Each part was mixed in a separate 8 L bottle and diluted by an independent injector. Potassium nitrate, calcium nitrate tetrahydrate and the iron chelate were mixed in the first bottle and ammonium phosphate monobasic, magnesium sulfate heptahydrate and all micronutrients were mixed in the second bottle. These solutions were divided in order to avoid precipitation problems with the high concentrations of the calcium, sulfate and phosphate-containing compounds used. On 12/5/05, the 2.0, 3.0 and 4.0 dS/m treatments were increased to 3.0, 4.5 and 6.0 dS/m, respectively, to hasten the progress of salt treatment effects. At this time, two concentrate bottles were used for each of the four salt treatment types. One bottle was used for the 1.0 and 3.0 dS/m treatments and the other was used for the 4.5 and 6.0 dS/m treatments (Figure 4). The Dosatron® DI-16 injector capabilities were limited such that two separate stock concentrations were required to deliver the range of target treatment concentrations.

Daily irrigations were scheduled with a Hunter® ICC irrigation timer (Hunter Industries Inc., San Marcos, CA). A leaching fraction of 0.4 to 0.5 was designed to be applied to all treatments independently. This fraction was employed to isolate symptoms related to the salt treatments by eliminating stress due to both insufficient water and increasing container EC due to evapotranspiration. Further, this leaching fraction was designed to provide sufficient irrigation treatment volume to allow for uniform saturation of the container medium.

Data Collection

Irrigation treatment solutions were evaluated on a weekly basis. One emitter tube at each tree was placed in a plastic bottle prior to the day's irrigation cycle to collect a sample of the treatment solution (Figure 5). After the irrigation cycle, a portable meter was used to test the EC of each sample and the solution was poured onto the potting medium surface. On the same day, leachate samples were collected. Tree pots were elevated on custom expanded metal stands (Dentoni's Welding Works, Inc., Stockton CA) and a plastic saucer was inserted below the stand, centered under the pot base

(Figure 5). After the treatment solution was poured onto the potting medium surface and the pot achieved container capacity (maximum water volume the potting medium could hold without further leaching from the container), a 45 mL sample was collected from each saucer and was analyzed in the laboratory for EC and pH.

Three growth parameters were regularly measured for each tree: trunk diameter, tree height and tree width. Trunk diameters were measured every second week starting on 9/25/05 and ending 1/3/07. A set of digital calipers (Fisher Scientific, Pittsburgh, PA) was placed around the trunk at a height of 3 cm above the potting medium in a constant orientation for each tree. The trunk was marked to indicate the points of contact for the calipers and the diameter was measured across these points each time. Tree height was evaluated every third week starting 9/15/05 and ending 1/8/07. Height was measured with a tape from an indicated point on the pot rim to the apex of the central leader of the tree (Figure 5). Tree width was determined every second week starting 11/16/05. Large articulating calipers were constructed to collect this data. These calipers were used to measure the distance between the western and easternmost lateral branch tips and the distance between the northern and southernmost lateral branch tips.

Five leaf tissue sampling events were scheduled at three to four month intervals during the experiment. Each sampling event was completed in two to five days. Dates of sampling completion were 10/17/05, 1/9/06, 5/18/06, 9/22/06 and 1/15/07. Shortly after the fifth sampling, the experiment was terminated. Consistency of tissue maturity was important in obtaining comparable results (Mills and Jones, Jr., 1991; West, J. R., pers. comm.). Therefore, only leaves produced during the previous flush of growth were selected for sampling. These leaves were identified as originating from lignifying stem segments occurring directly behind the youngest, light green leaves on solid green stems. Stem segments were further distinguished by noting their relative leaf length. If measured acropetally along the stem segment, the relative leaf length increased, reached a maximum and then decreased. Segments were selected around each tree, from the lowest branches to the tallest branches.

Both proximal (P) and distal (D) leaf blade sections were collected on each date. Leaf blades on the appropriate segments were transversely cut in half, first collecting the distal section (Figure 6). The halfway cut point was determined visually. As redwood leaves do not have discernible petioles, the proximal section was then removed by cutting the leaf from the stem as close to the stem as possible (Figure 6). Typically, both proximal and distal sections were collected from the same stem segments. A minimum of 1.47 g dry weight (3.75 g fresh weight, 39 % dry: fresh weight ratio) was collected for each sample. The day following sampling completion, samples were shipped via courier to Dellavalle® Laboratory, Inc. (Fresno, CA). Leaf samples were analyzed for ppm B, % Ca, % Cl, ppm Cu, ppm Fe, % K, % Mg, ppm Mn, % Na, % P and ppm Zn. This report will present the results for % Ca, % Cl and % Na. Calcium and Na were analyzed with the "Nitric / Perchloric Wet Ashing Open Vessel" (P – 3.10) technique and Cl was analyzed using the "2% Acetic Acid Extraction" (P – 4.20) technique of Gavlak *et al.*, 2003.

Digital photographs collected at each tissue sampling were used to track the symptom development of each plant. Pictures included a whole-plant image and close-up images of a specific primary branch, secondary branch and the apex of the central leader of each tree. A primary branch initially scored as healthy and free of damage was selected and tagged for photographic purposes. An image of this branch and one of the secondary branches attached to it were photographed on each picture collection date. This report will present the pertinent photographs taken on 1/10/07, prior to the final sampling event.

Results

Treatment solution EC varied slightly over the duration of the experiment. The greatest variant from the target EC was observed with the NaCl, 6.0 dS/m treatment, with a mean finalized EC (12/7/2005 to 1/9/2007) of 5.72 ± 0.08 dS/m (Table 3). Increasing treatment EC produced an increasingly greater leachate EC.

The increase in treatment EC from 2.0, 3.0 and 4.0 dS/m to 3.0, 4.5 and 6.0 dS/m, respectively, was apparent beginning on 12/5/05 (Figure 7). Variation in treatment EC occurred between 3/06 and 6/06, most notably for the three highest EC treatments within each salinity type. Treatment solution pH did not vary greatly by salinity type or concentration (Table 4).

Leachate EC for each treatment increased relative to the application EC (Figure 8). As treatment EC increased from 1.0 to 6.0 dS/m, the corresponding leachate EC differed by an increasing value. The control treatment leachate EC increased by approximately 20 % of the applied value. For each salt, the leachate EC from the 3.0 dS/m treatment was approximately twice as high as that from the 1.0 dS/m treatment. For the 4.5 and 6.0 dS/m $CaCl_2$ and NaCl + $CaCl_2$ salinity treatments, the leachate EC increased to approximately 8 and 10 dS/m, respectively. The 4.5 and 6.0 dS/m NaCl and Na_2SO_4 treatments produced leachate EC values of approximately 6.0 and 8.0 dS/m, respectively. Beginning in August of 2006 several saucers remained empty during a weekly leachate collection event, indicating that the designed leaching had not occurred (17 empty saucers in all from 8/06 to 1/07, less than 1 % of all samples collected during this period). The majority of these events occurred within the control and 1.0 dS/m salinity treatments and most events did not occur to the same replicate more than once.

Leachate pH values segregated by treatment as the experiment progressed (Figure 9). As treatment EC increased within a salinity type, the resulting leachate pH decreased. The NaCl and Na_2SO_4 salinity types yielded leachate values over a narrower pH range than the $CaCl_2$ and NaCl + $CaCl_2$ salinity types. All treatment leachate pH values were on average higher than the pH of the respective application solution (Table 4, Figure 9).

Mean relative trunk diameter values diverged by treatment until November 2006, most notably between the 1.0 dS/m treatment and the 3.0, 4.5 and 6.0 dS/m treatments (Figure 13). The relative trunk diameters of the 1.0 dS/m treatment of all salt types, with the exception of Na_2SO_4, closely followed those of the control treatment. The greatest change in relative trunk diameter for all treatments occurred during the period of April 2006 through November 2006, whereas the least change in relative trunk diameter occurred between December 2005 and February 2006. In general, as treatment EC increased within a salinity type, trunk diameter growth relative to 9/25/05 decreased. Five values, less than 0.2 % of all values, were removed from this dataset over the duration of the experiment due to measurement error. Specific replicates were not affected more than once. An analysis of variance (ANOVA) using the GLM procedure in SAS 9.1 (SAS Institute Inc., Cary, NC) on trunk diameter from 1/3/07 relative to 9/25/05 revealed a significant block and highly significant treatment effect at the 95 % confidence level (Table 5). On 1/3/07, the control trunk diameter relative to 9/25/05 was significantly greater than the 3.0, 4.5 and 6.0 dS/m treatments of all salinity types (Figure 11). Though not different from the control, the 1.0 dS/m NaCl and NaCl + $CaCl_2$ treatments were both different from the 3.0, 4.5 and 6.0 dS/m treatments within their respective salinity type. No differences were detected between any salinity treatments within the same EC level. Further, a significant difference was only detected in the Na_2SO_4 salt type between the 3.0, 4.5 and 6.0 dS/m treatments. Mean trunk diameter collected on 1/3/07 is presented in Appendix 1.

Increasing meq Na/L due to the four concentrations applied caused a decreasing trend in mean relative trunk diameter within a salinity type over the four concentrations applied (Figure 12). The $CaCl_2$ treatments displayed a decrease over the four treatment concentrations as well, although solution Na concentration in these treatments was zero. The NaCl + $CaCl_2$ treatments displayed a similar decrease in mean relative trunk diameter over the four concentrations, but the milliequivalents (meq) of Na/L were approximately 1/3 of the values of the other Na-containing salinity types at the same EC. The Hoagland's nutrient solution did not contain Na and, therefore, did not contribute this ion to any treatment (Table 1).

Increasing treatment meq Ca/L due to the treatments caused a similar decreasing trend in mean relative trunk diameter within a salinity type (Figure 13). The NaCl and Na_2SO_4 treatments displayed a decrease over the four treatment concentrations as well, although the meq Ca/L for these treatments was zero. The NaCl + $CaCl_2$ treatments displayed a similar decrease in mean relative trunk diameter over the four concentrations, but the meq Ca/L were approximately 2/3 of the values of the $CaCl_2$ salinity treatments at the same EC. The calcium contribution by the base nutrient solution was 1.70 meq/L (Table 1).

The influence on trunk diameter of both major cations combined (meq (Na + Ca)/L) is shown in Figure 14. The resulting slopes for mean relative trunk diameter for the four salinity types over the four meq concentrations of Na + Ca applied are very similar (-0.02) (Figure 15). The R^2 values for the control and four concentrations within each salinity type range from 0.72 for the $CaCl_2$ treatments to 0.81 for the Na_2SO_4 treatments. The Y-intercept values range from 2.69 for the Na_2SO_4 treatments to 2.80 for the NaCl + $CaCl_2$ treatments. Mean trunk diameter was similarly influenced by the total salinizing anions (Cl + SO_4) in one solution (Figure 16). Slopes and intercepts are clearly shown in the figures.

Mean relative tree height values and the corresponding standard errors overlap greatly (Figure 17). In general, as treatment EC increased within a salinity type, tree height relative to 9/15/05 decreased. Eight values were removed from this dataset over the duration of the experiment (less than 0.4 %) due to measuring inaccuracies. Some replicates were affected several times. Replicate 1-4 (control treatment) was permanently removed from height data collection beginning 1/26/06. Data points were removed for the NaCl + $CaCl_2$ 1.0 dS/m treatment from 7/10/06 to 9/14/06, for the $CaCl_2$ 1.0 dS/m treatment for 10/3/06 and for the Na_2SO_4 1.0 dS/m treatment for 8/24/06. An ANOVA using the GLM procedure in SAS on tree height from 1/8/07 relative to 9/15/05 produced a nonsignificant block and significant treatment result at the 95 % confidence level (Table 5). On 1/8/07, the control tree height relative to 9/15/05 was significantly greater than the 6.0 dS/m treatments of the NaCl and Na_2SO_4 salinity types (Figure 18). No statistical differences in relative tree height were detected within the $CaCl_2$ or NaCl + $CaCl_2$ irrigation treatments. Mean tree height collected on 1/8/07 is presented in Appendix 1.

Intermediate concentrations of meq (Na + Ca)/L caused the most variation in relative tree height (Figure 19). Without regard to salinity type, means of all 17 treatments showed a decrease in relative height over the range of meq (Na + Ca)/L concentrations. Regression of relative tree height calculated for each replicate on 1/8/07 compared to 9/15/05 yielded slopes ranging from -0.01 to -0.02 over the four salinity types and four concentrations imposed when graphed by treatment meq (Na + Ca)/L (Figure 20). The R^2 values for the control and four concentrations within each salinity type ranged from 0.19 for the NaCl + $CaCl_2$ treatments to 0.38 for the NaCl treatments. The Y-intercept values ranged from 2.22 for the NaCl + $CaCl_2$ treatments to 2.39 for the Na_2SO_4 treatments.

Tree width measurement activities were terminated in 4/2006 as this measurement proved to be too variable to obtain discernible results.

Over the five leaf tissue sampling dates, the control treatment demonstrated a slight decrease in % Na (Figure 22). The large standard error for the proximal value on 9/22/06 was caused by a single out-of-proportion value. There were no apparent differences in leaf section Na content on any sampling date. Four outliers were identified and removed from the % Na tissue analysis. These values represented less than 0.4 % of the total data analysis.

Leaf Na concentrations within the NaCl salinity type showed differences in accumulation over the five dates tested (Figure 23). On the second sampling date, 1/9/06, the leaf sections of the 1.0 dS/m treatment contained less Na than those receiving the three higher concentrations. The 1.0 dS/m treatment leaf % Na remained lower than the other NaCl treatments for the three final sampling dates as well. In addition, the Na content of leaves receiving the 3.0, 4.5 and 6.0 dS/m treatments diverged from the content of those exposed to the control treatment on 1/9/06, while the 1.0 dS/m treatment remained equal to the control values (Figures 22, 23). On 5/18/06, the NaCl 4.5 and 6.0 dS/m treatments diverged from NaCl 3.0 dS/m treatment. On 9/22/06, all treatments were distinguishable, with % Na leaf content increasing with increasing treatment EC. Few differences in Na content were apparent on 1/15/07 relative to 9/22/06. An unusually low proximal value in one replicate caused the % Na difference in the proximal and distal sections of the NaCl 3.0 dS/m section on 1/15/07. Few proximal and distal differences in leaf % Na were observed within a specific date and treatment. When differences were detected, the distal section content was greater than the content in the proximal section.

All $CaCl_2$ treatments demonstrated a decrease in leaf tissue % Na over the five sampling dates (Figure 24). The change became apparent on 5/18/06 and decreased to the minimum observed on 9/22/06. No difference was observed in % Na between 9/22/06 and 1/15/07. The leaf % Na in the $CaCl_2$ treatments was the same as that observed in the control treatment (Figures 22, 24).

The NaCl + $CaCl_2$ treatments displayed a lower level of Na leaf accumulation relative to the NaCl treatments over the experiment duration (Figures 23, 25). The Na leaf content resulting from the NaCl + $CaCl_2$ 1.0 dS/m treatment was comparable to that of the $CaCl_2$ treatments for the first three sampling dates, but maintained a higher concentration on the fourth and fifth dates (Figures 24, 25). Sodium leaf content in the $NaCl + CaCl_2$ 3.0, 4.5 and 6.0 dS/m treatments was not distinguishable when compared within each sampling date. These values were comparable to the % Na in the NaCl 1.0 dS/m treatment on each date (Figures 23, 26).

Sodium leaf content of the Na_2SO_4 1.0 and 3.0 dS/m treatments did not notably differ from the corresponding NaCl 1.0 and 3.0 dS/m treatments (Figures 23, 26). On the fourth sampling date, 9/22/06, a difference was observed in % Na between the NaCl and Na_2SO_4 4.5 and 6.0 dS/m treatments. These NaCl treatments acquired more Na by this date than the respective Na_2SO_4 treatment. Unlike the NaCl treatments, the Na_2SO_4 4.5 and 6.0 dS/m treatments continued to accumulate more Na between the fourth and fifth sampling dates. The leaf Na content of the highest three Na_2SO_4 concentrations were very similar within each sampling date. Mean leaf sodium content of all dates, treatments, sampling dates and sections are presented in Appendix 2.

Control treatment leaf % Cl did not change over the duration of the experiment (Figure 27). The relatively large error bar on the 1/15/07 proximal bar was caused by a single atypically large value. No differences were detected between Cl content of the proximal and distal sections. Eleven outlier values were identified and removed from the % Cl analysis. These values represented less than 1.1 % of the total data points in this analysis.

The NaCl treatment set did not begin to cause differences in % Cl leaf content until the third sampling date, 5/18/06 (Figure 28). The 1.0 dS/m treatment % Cl values did not differ until 9/22/06. Differences between the fourth and fifth dates were observed within the 4.5 dS/m proximal and distal section values and within the proximal 6.0 dS/m values. Several abnormally high values caused elevated means and SE bars in the NaCl set, specifically in the 4.5 dS/m proximal section on 1/15/07 and the 6.0 dS/m proximal and distal sections on 5/18/07.

Chloride leaf content in the $CaCl_2$ treatments did not cause a difference until 5/18/06 (Figure 29). With exception to the distal section on 1/15/07, % Cl in the 1.0 dS/m treatment did not change over the experiment duration. The top three concentrations could not be distinguished with relation to Cl accumulation. By 1/15/07, the leaf sections of the 3.0 and 6.0 dS/m $CaCl_2$ treatments had accumulated less Cl than the 3.0 and 6.0 dS/m NaCl treatments on the same date (Figures 28, 29).

The 1.0 dS/m NaCl + $CaCl_2$ treatment did not begin to differ in % Cl until 9/22/06 (Figure 30). The large proximal mean and error bar on the 1/15/07 NaCl + $CaCl_2$ 1.0 dS/m and 9/22/06 4.5 dS/m proximal treatments were caused by one atypically large value for each. The 6.0 dS/m treatment acquired more chloride than the other concentrations by 5/18/06. By the fifth date, this difference was not as apparent. Percent chloride did not change for any of the Na_2SO_4 treatments over the date sampled (Figure 31). These % Cl values were the same as the control treatment % Cl values.

Leaf calcium concentration in the control treatment did not vary over the experiment duration (Figure 32). Six outlier values were identified and removed from the % Ca analysis. These values represented less than 0.6 % of the total data points in this analysis. Mean leaf chloride content of all dates, treatments, sampling dates and sections are presented in Appendix 3.

The leaf Ca content due to the 1.0 dS/m NaCl treatment displayed results similar to the control values (Figure 33). Several proximal sections contained a greater amount of Ca than their corresponding distal sections. The NaCl 4.5 and 6.0 dS/m treatment % Ca values decreased on 9/22/06 relative to the other dates in these treatments.

Calcium leaf content in the $CaCl_2$ treatments increased steadily over the experiment duration (Figure 34). The 3.0, 4.5 and 6.0 dS/m $CaCl_2$ treatments caused similar increases in leaf Ca content. The 1.0 dS/m treatment demonstrated a lower level of Ca accumulation relative to the higher three concentrations beginning on 5/18/06.

The NaCl + $CaCl_2$ treatments did not cause leaves to accumulate Ca to the level of the $CaCl_2$ treatments (Figures 34, 35). The NaCl + $CaCl_2$ 3.0, 4.5 and 6.0 dS/m treatments were not distinguishable (Figure 35). The 1.0 dS/m treatment demonstrated lower leaf % Ca on dates 5/18/07, 9/22/07 and 1/15/07.

Calcium leaf content of trees exposed to the Na_2SO_4 treatments was also similar to the control values (Figure 36). However, the 9/22/06 dates demonstrated several values lower in Ca than the control and the other sampling dates for the Na_2SO_4 treatments. Mean leaf calcium content of all dates, treatments, sampling dates and sections are presented in Appendix 4.

On the final sampling date, 1/15/07, % Na for all four $CaCl_2$ treatments was equal to that of the control treatment (Figure 37). Leaf % Na demonstrated the largest differences between the control and the 1.0 and 3.0 dS/m level of any Na-containing treatments. The 3.0, 4.5 and 6.0 dS/m levels of any Na-containing treatments demonstrated the most similar values within each of those salinity types. However, the Na_2SO_4 3.0 dS/m leaf sections contained less Na than the 6.0 dS/m treatment on 1/15/07. Leaf sodium content of the NaCl + $CaCl_2$ treatments was less that the Na content of the other Na-containing treatments. Few proximal-distal differences were apparent.

The NaCl 6.0 dS/m treatment caused more Cl leaf accumulation than the 6.0 dS/m $CaCl_2$ treatment (Figure 38). The proximal section of the NaCl 6.0 dS/m treatment had a greater Cl content than either section of the NaCl + $CaCl_2$ 6.0 dS/m treatment. The other Cl-containing treatments were indistinguishable within EC level with exception to the proximal NaCl + $CaCl_2$ 4.5 dS/m section, which accumulated less Cl than the other salinity treatments of the same EC. Chloride content in the Na_2SO_4 treatments on 1/15/07 did not differ from the control treatment.

Within each concentration, the $CaCl_2$ treatments caused more leaf Ca accumulation than the NaCl + $CaCl_2$ treatments (Figure 39). No difference in Ca content was determined in leaves of the 4.5 dS/m and 6.0 dS/m treatments of any salinity type. The NaCl and Na_2SO_4 treatment leaf % Ca values were similar to the control values in content than to the Ca-containing salinity type treatments. Several leaf sections of the 3.0, 4.5 and 6.0 dS/m concentrations within these salinity types accumulated less Ca than the control.

Secondary branches of each control plant on 1/10/07 exhibited light tip burn symptoms (Figure 40). Tip burn developed on leaves of all ages and across all flushes of growth. Replicate 1-1 demonstrated necrotic spotting on the fresh leaves and stems. This symptom rarely occurred on the other replicates within the control treatment.

The NaCl 1.0 dS/m trees (Figure 41) displayed a level of leaf tip necrosis that was not distinguishable from the control (Figure 40) or other 1.0 dS/m trees (Figures 45, 49 and 53). This symptom was present across all flushes of growth. The dead branch segment in the bottom right of figure 41 did not originate from the replicate photographed. At the 3.0 dS/m concentration, a significant increase in leaf damage over the 1.0 dS/m and control trees was apparent (Figure 42). Necrosis began at the leaf tip and progressed in the basipetal direction. Damage was focused primarily on the most recent growth flushes and entire leaves and stem segments in this region were occasionally killed. Stem segments at the branch tips in the NaCl 4.5 dS/m treatment were regularly killed and the necrosis in this treatment affected a larger proportion of complete leaves from previous growth flushes (Figure 43). The images from the 6.0 dS/m NaCl treatment trees were not distinguishable from those of the 4.5 dS/m treatment (Figures 43, 44). The majority of replicate tree 5-3 was dead by 1/10/07.

Leaf tip necrosis on the $CaCl_2$ 1.0 dS/m treatment replicates (Figure 45) was not different from the control (Figure 40) or other 1.0 dS/m treatments (Figures 41, 49 and 53). Symptoms were regularly present on leaves of all ages. The 3.0 dS/m trees (Figure 42) demonstrated a similar level of necrosis to the 3.0 dS/m trees of the other salinity types except the NaCl + $CaCl_2$ 3.0 treatment (Figures 46, 54). Appearance of the $CaCl_2$ 4.5 dS/m and 6.0 dS/m trees (Figures 47, 48) were not different and were similar to the NaCl and NaCl + $CaCl_2$ trees of the same electrical conductivities (Figures 43, 44, 51 and 52). Frequently, necrosis on the 3.0, 4.5 and 6.0 dS/m $CaCl_2$ trees would exhibit a much redder color than the necrotic tissue on the 3.0, 4.5 and 6.0 dS/m trees not receiving $CaCl_2$.

Symptoms on the NaCl + $CaCl_2$ 1.0 dS/m treatment (Figure 49) replicates were similar to the control and other 1.0 dS/m treatments (Figures 40, 41, 45 and 53). The NaCl + $CaCl_2$ 3.0 dS/m trees demonstrated lighter symptoms than the other 3.0 dS/m treatment trees (Figures 42, 46, 50 and 54), but this treatment showed more leaf damage than seen in the NaCl + $CaCl_2$ 1.0 dS/m treatment (Figure 49). Fewer complete leaves and terminal stem sections showed damage at this concentration with the NaCl + $CaCl_2$ salinity type. Leaves and stem sections in the NaCl + $CaCl_2$ 4.5 and 6.0 dS/m treatments (Figures 51, 52) were not distinguishable in damage level from the NaCl and $CaCl_2$ trees at the same concentrations (Figures 43, 44, 47 and 48). The NaCl + $CaCl_2$ 3.0, 4.5 and 6.0 dS/m trees displayed the same reddish necrotic tissue as seen in the $CaCl_2$ treatments.

At the 1.0 dS/m concentration (Figure 53), the Na_2SO_4 salinity type did not visually affect the leaves and stems differently than the control and other 1.0 dS/m treatments (Figures 40, 41, 45 and 49). Similarly, the Na_2SO_4 3.0 dS/m treatment (Figure 54) was not different from the NaCl and $CaCl_2$ 3.0 dS/m salinity type treatments. The trees exposed to both the 4.5 and 6.0 dS/m Na_2SO_4 treatments exhibited heavier damage than trees irrigated with the other salinity treatment solutions at these electrical conductivities (Figures 55, 56). Many complete primary branches were dead by 1/10/07. Surviving secondary and tertiary branches were epinastic. One replicate in the 4.5 dS/m treatment and three in the 6.0 dS/m treatment were dead by 1/10/07.

Discussion

Treatment solution variation was caused by several factors. The decrease in treatment EC of the Na_2SO_4 solutions immediately after the initiation of the experiment was caused by precipitation of Na_2SO_4 in the concentrate stock bottles. As less Na_2SO_4 remained in solution, the stock concentration decreased leading to a decrease in the concentration of the treatment solution. This event was stimulated by both the high concentrations of these stock solutions and the decreasing night temperatures in the greenhouse. To remedy the issue, aquarium heaters were installed in Igloo coolers (Igloo Products, Inc., Katy, TX), the stock bottles were placed in the coolers and the coolers were filled with water. Water temperature in the coolers was controlled by the heaters and was maintained above the critical precipitation temperature, as determined by consulting a figure demonstrating the relationship between Na_2SO_4 solubility and temperature (Wikipedia: The Free Encyclopedia). Submersible pumps and flexible tubing provided heated water for the Dosatron® concentrate supply lines as well as for the base of the injector units to assure no precipitation occurred in these locations. Heated water lines, supply lines and the base of the injector units were wrapped with insulation. Between 3/06 and 6/06, all treatment solutions rose and fell in a similar pattern. The change in concentration increased as the treatment EC increased. The only common factor to all the injectors and treatments was the demineralized water supply line. Although a pressure regulator was installed upstream of the injector units, changes in supply pressure may have caused the EC variation observed. However, all treatments remained very distinct over the experiment duration, with few exceptions. The main factor affecting treatment pH was the 0.5 dS/m Hoagland's solution, which contained several acidic ingredients (Table 1).

Leachate EC tracked closely within a salinity type. Values rose and fell together over time. This was most likely due to changing evapotranspiration, influenced by both the changing greenhouse environment over the seasons and the growth of the trees.

Although the plants were greenhouse-grown, relative trunk diameter was affected by the seasons. The largest increases in relative diameter over time were observed between the months of April and November 2006 (Figure 10). The largest effects (decreases) in relative trunk diameter were observed between the 1.0 and 3.0 dS/m treatments for the NaCl, $CaCl_2$ and NaCl + $CaCl_2$ treatments. As EC increased, the effect on relative trunk diameter for these treatments decreased. When comparing the decrease between the 3.0 and 6.0 dS/m treatments, the differences in relative trunk diameter appeared similar. However, the difference between the 1.0 and 3.0 dS/m treatments is 2 dS/m, while the difference between the 3.0 and 6.0 dS/m treatments is 3 dS/m. The significant differences detected from the final trunk diameter collection date relative to the first collection date further emphasize the significance of the salt concentrations at the 1.0 dS/m level (Figure 11). From low to high EC, the first significant differences detected within a salt type between treatments other than the control occurred in all cases between the 1.0 dS/m treatments and either the 3.0 or the 4.5 dS/m treatments.

When relative trunk diameter was plotted against the meq of the major cationic constituents present in the salinity treatments, Na and Ca, the response was similar regardless of cation composition (Figure 14). Whether the major cationic constituent was sodium, calcium, or an equimolar combination of each, the resulting effect on relative trunk diameter was equivalent, as indicated by identical slopes and high R^2 values within all four salinity types (Figure 15). Relative trunk diameter plotted against the major anions present in the salinity treatments, Cl and SO_4, gave similar results (Figure 16).

Standard error for relative tree height was more variable than relative trunk diameter standard error. Several issues were encountered while collecting tree height measurements that contributed to this variability. At times, trees would push a competing leader (resulting in a secondary leader) that would be mistakenly measured. As trees increased in height, the apex became more difficult to measure accurately. Ladder use on an unleveled floor and flexibility of the central leader contributed to further variation in height measurement. In addition, this characteristic may have been inherently more variable than trunk diameter. Shading, greenhouse positioning and the sucker-producing tendency for many of the trees most certainly also contributed to the increased variability. Some suckers would grow 20 cm vertically in two months, while over the same period the proper shoot tip did not grow. This vigorous suckering differed by individual specimen and appeared to be independent of treatment or location. Mean values were removed on several dates due to incorrectly measured replicates. Typically, the one problematic replicate contributing to the treatment mean was one of the taller trees in the treatment. When this replicate value was removed, the mean appeared disproportionately low relative to mean values in the same treatment on surrounding dates. Due to this appearance and lack of relevance, the mean value was omitted from the graph.

Less seasonal change in relative height was apparent over time than the seasonal change with relative trunk diameter due to the increased variability in this dataset (Figures 9, 17). Relative height of the 1.0 dS/m treatments were not different from any other treatments (Figure 18).

Several trees grew tall enough to touch the greenhouse roof during the experiment. The greenhouse roof was sloped and the peak was oriented east-west and to the south of center across the two blocks. As trees encroached within 15 to 20 cm of the glass ceiling, they were exchanged with another tree in another location (Figure 21). Four parameters were imposed when selecting the exchange tree. First, the exchange tree must be shorter than the tree in close proximity to the ceiling. Second, the exchange tree must be positioned closer to the center of house (to allow more vertical space for growth). Third, the tree must be close to the same north-south positioning as the encroaching tree and within the same experimental block. Fourth, the tree meeting these parameters would ideally be a replicate of the same salinity type and EC as the encroaching tree. If a replicate meeting these four parameters could not be located, one meeting the first three was selected with no attention to salinity type or concentration. In this case, tubing and emitters were re-plumbed to deliver the appropriate treatments to both trees. In all, 17 trees attained a height that required relocation, resulting in 34 total trees moved.

Relative tree height was weakly correlated with the meq of the major cations in the salinity treatments, Na and Ca (Figures 19, 20). Slopes were very comparable, differing by only 0.01, but the low R^2 correlation in all cases made discussion regarding the concentration effects on relative tree height dubious.

Tree width variability was caused by both inter-tree competition for light and occasional suckering activity. As many lateral branches lengthened, they became pendant. Other vigorous lateral branches expressed a strong positive phototropic or negative gravitropic response, bending them upwards. These changing habits at times affected a lateral branch 10 – 20 cm basipetal from the tip, resulting in redirection of the shoot tip and a decrease in previously measured tree diameter. Vigorous lateral branches were also observed to change horizontal direction in response to shading by branches from surrounding trees. The articulating calipers constructed for measuring this parameter were accurate to ± 1 cm.

In response to the Na-containing treatments, the largest difference in leaf Na concentration occurred between the 1.0 dS/m and the 3.0 dS/m treatments. Accumulation rate increased as treatment concentration increased. The control and $CaCl_2$ treatments both demonstrated decreases in % Na over time due to the lack of this ion in these treatments. Proximal and distal sections were not different (Figures 22-26).

Increased air movement through several plants in block two was theorized to be the cause of the outlier values identified. The plants affected were in proximity to the two large cooling fans on the east wall of this block and it was theorized that an increased transpiration rate in these plants due to greater air movement contributed to the abnormally high ion concentrations observed. Outlier values were identified by studying the "Extreme Observations" output from the "proc normal" procedure in the corresponding statistical analysis in SAS. In order to qualify for exclusion from the analysis, the extreme observation must have met two qualifications. First, the value must have originated from a tree in proximity to the cooling fans. Second, only abnormally high results relative to the others from the same salt treatment qualified for removal. Abnormally low results, which occurred much less frequently, could not be explained with the theory described.

Leaf Cl accumulation was comparable to that of Na. The 1.0 dS/m concentrations of the Cl-containing treatments demonstrated an overall lower level of Cl accumulation relative to the three higher treatment concentrations (Figures 28-30), with exception of the proximal 1.0 dS/m NaCl + $CaCl_2$ treatment. Chloride accumulation increased as treatment concentration increased. However, differences between treatment concentrations were not apparent until the third sampling on 5/18/06. By the final sampling date, 1/15/07, most of these differences had disappeared. Leaf proximal and distal sections were not different (Figures 27-31).

Leaf Ca in the Ca-containing treatments also differed between the 1.0 dS/m and higher concentrations (Figures 34-36). All treatments contained Ca if only at base nutrient levels. No differences in leaf Ca were apparent until the third date, 5/18/06, when the 3.0, 4.5 and 6.0 dS/m treatments of the Ca salinity treatments diverged from the 1.0 dS/m treatment. Leaf proximal and distal sections were not different (Figures 32-36).

Differences in Na, Cl and Ca uptake due to the 1.0 and 3.0 dS/m treatments are shown in Figures 37-39. For all three ions, the largest difference in accumulation was observed between the 1.0 and 3.0 dS/m treatments for salinity types containing the ion for which they were tested (Figures 37-39). This observation was not as clear for % Cl in the 1.0 and 3.0 dS/m NaCl + $CaCl_2$ treatments. Further, the presence of Ca may have decreased Na uptake in the NaCl + $CaCl_2$ treatments. The concentrations of Na in the NaCl + $CaCl_2$ treatments were approximately 34 % of the meq Na in the NaCl treatments. However, % Na in the NaCl + $CaCl_2$ treatments was only approximately 25 % of the Na in the NaCl treatments (Figure 37).

Although several photographs were taken from each tree, the secondary branch images proved to be the highest quality and most descriptive. Secondary branch images of all salinity types clearly show the difference between the 1.0 and 3.0 dS/m treatments. The 3.0 dS/m concentration for all treatments was the lowest concentration where a visual distinction could be made with the symptoms of the control treatment. It is not understood why more trees died in the 6.0 dS/m Na_2SO_4 treatment than in the other treatments of the same EC.

A correlation may exist between leaf necrosis in the 4.5 and 6.0 dS/m treatments and the concentration and/or exposure time of the salinity types utilized. The majority of the leaves photographed on 1/10/07 and sampled on 1/15/07 in the 4.5 and 6.0 dS/m treatments were dead. In addition, within a salinity type and an ionic analysis on this date, % Na, % Cl and % Ca for these two treatments could rarely be distinguished

(Figures 37-39). On 1/15/07, the 3.0 dS/m treatments displayed more differences with the two higher treatments than they did between them and the 1.0 dS/m treatments were most all different from these two treatments. Most tissue results followed the same pattern, with decreasing damage as treatment concentration decreased to the 1.0 dS/m level. Given more exposure, it is not known whether the 1.0 and 3.0 dS/m concentrations may ultimately have achieved the same level of tissue content and damage as the 4.5 and 6.0 dS/m concentrations.

Conclusions

The response of *Sequoia sempervirens* 'Aptos Blue' to the salinity treatments in this study indicates a clear increase in detrimental effect with increasing treatment concentration. Although initially included as counter ions to isolate Na and Cl responses, both the Ca and SO_4-containing treatments had similar detrimental effects to the NaCl treatments. The NaCl + $CaCl_2$ treatments did not exhibit a reprieve over the NaCl treatments. Based on the equal slopes and R^2 values obtained in the total cationic concentration vs. relative trunk diameter data and the plant photographs collected on 1/10/07, the effects of the salinity treatments on the redwood trees were more related to total salinity rather than to specific ion effects. No distinction can be made between Na effects and Cl effects. The tissue analyses included are most useful in determining leaf tissue concentrations at which undesirable visual symptoms occur- whether they are decreased trunk diameter and height, or leaf necrosis and tree death. Although very few differences between proximal and distal sections were noted, if these results are used to compare with whole-leaf tissue results obtained elsewhere, the following equation can be used to convert the proximal and distal tissue results to a whole leaf value for a particular element:

Whole leaf mean = (Proximal leaf mean + Distal leaf mean) / 2

Both the trunk diameter analysis and visual leaf symptom monitoring demonstrated no differences between the control and 1.0 dS/m treatment levels. However, the 3.0 dS/m treatments are largely different from those two treatment levels. Thus, water that will maintain the soil solution at an EC close to 1.0 dS/m would appear to decrease the likelihood of producing detrimental symptoms on redwood trees irrigated with recycled water. Recycled water quality with relation to this chemical aspect does not appear to be the principal issue causing the redwood decline noted in the greater South Bay. Even at the relatively low conductivity of 1.0 dS/m, salt can accumulate in the soil profile if proper leaching is not employed to carry the salts out of the root zone. This study intentionally employed a high leaching fraction to minimize salt accumulation in the pots. It is clear that redwoods can tolerate EC values in the range typical for recycled waters if irrigation is properly managed.

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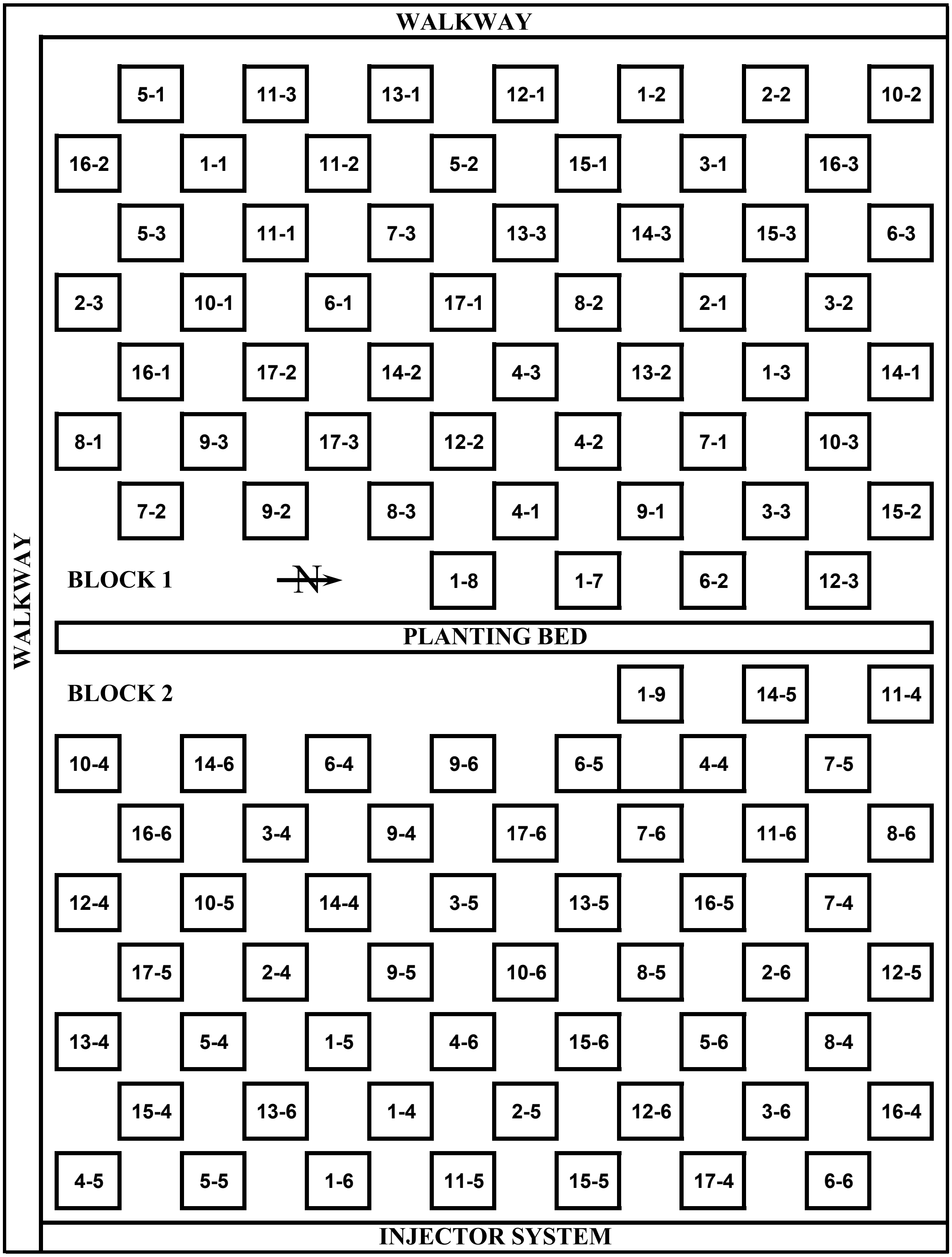

Figure 1. Greenhouse map. Numbered squares designate treatment-replicate identification and position for each tree.

Table 1. Treatment 1: Modified Hoagland's solution composition, 0.5 dS/m.

Component	g/L	meq/L Na	meq/L Cl	meq/L Ca
$NH_4H_2PO_4$	0.024			
KNO_3	0.13			
$Ca(NO_3)_2{\cdot}4H_2O$	0.20			1.70
$MgSO_4{\cdot}7H_2O$	0.10			
H_3BO_3	0.00061			
$MnCl_2{\cdot}4H_2O$	0.00039		0.0039	
$ZnSO_4{\cdot}7H_2O$	0.000047			
$CuSO_4{\cdot}5H_2O$	0.000017			
$H_2MoO_4{\cdot}H_2O$	0.0000043			
Iron chelates: ETDA, citric acid	0.00060			

Table 2. Treatments 2-17: Salinity treatment composition.

Trt. no.	Salinity type	EC (dS/m)*	Component	g/L	meq/L Na	meq/L Ca#	meq/L Cl#	meq/L SO_4#
2	NaCl	1.0	NaCl	0.25	4.38	1.70	4.39	0.85
3		3.0		1.33	22.91	1.70	22.92	0.85
4		4.5		2.19	37.71	1.70	37.71	0.85
5		6.0		3.05	52.56	1.70	52.57	0.85
6	$CaCl_2{\cdot}2H_2O$	1.0	$CaCl_2{\cdot}2H_2O$	0.33	0.00	6.28	4.58	0.85
7		3.0		1.70	0.00	24.95	23.26	0.85
8		4.5		2.87	0.00	40.91	39.21	0.85
9		6.0		3.97	0.00	56.03	54.33	0.85
10	NaCl + $CaCl_2{\cdot}2H_2O$	1.0	NaCl	0.09	1.51	4.72	4.54	0.85
			$CaCl_2{\cdot}2H_2O$	0.22				
11		3.0	NaCl	0.46	7.93	17.43	23.66	0.85
			$CaCl_2{\cdot}2H_2O$	1.15				
12		4.5	NaCl	0.75	12.85	27.36	38.51	0.85
			$CaCl_2{\cdot}2H_2O$	1.88				
13		6.0	NaCl	1.06	18.22	38.09	54.60	0.85
			$CaCl_2{\cdot}2H_2O$	2.66				
14	Na_2SO_4	1.0	Na_2SO_4	0.35	4.98	1.70	0.0039	5.83
15		3.0		1.82	25.63	1.70	0.0039	26.48
16		4.5		2.98	41.99	1.70	0.0039	42.84
17		6.0		4.29	60.37	1.70	0.0039	61.21

*Includes 0.5 dS/m contributed by Hoagland's solution

#Includes meq/L contributed by 0.5 dS/m Hoagland's solution

Figure 2. Tree organization, irrigation treatment delivery and expanded metal pot stands.

Figure 3. Injector system. Red cans intended for concentrate tanks were replaced with 8L bottles.

Figure 4. Eight liter concentrate bottle supplying two injectors. Concentrate solution was agitated by pressurized air delivered through 0.635 cm black tubing.

Figure 5. Saucer under pot stand for leachate collection and bottle for irrigation treatment collection.

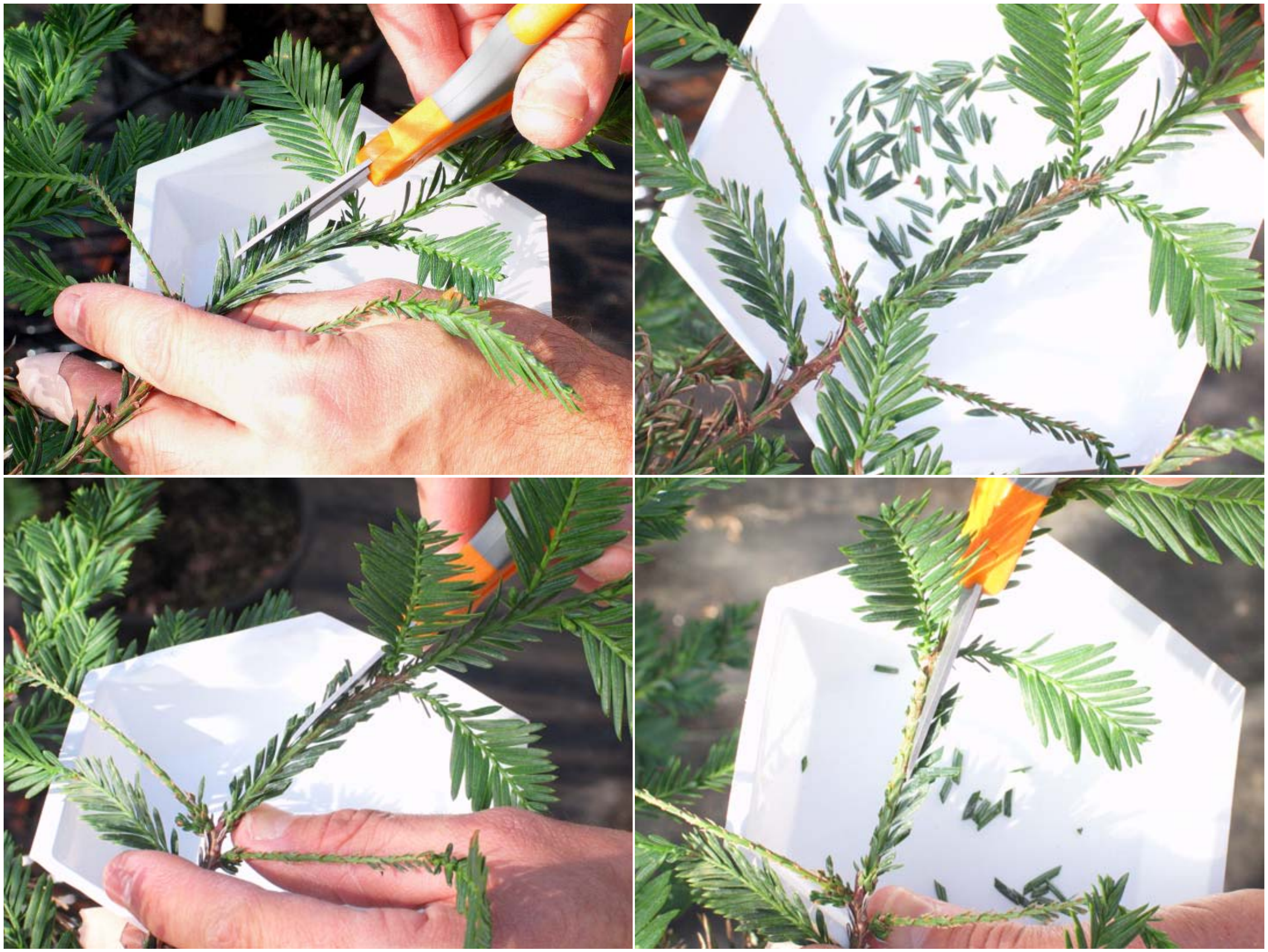

Figure 6. Leaf sampling procedure. Proximal leaf sections were collected and packaged first, followed by distal sections.

Table 3. Mean finalized treatment and leachate EC values.

Trt. no.	Salinity treatment and target EC	Mean treatment EC (dS/m) ± 1 SE	Mean leachate EC (dS/m) ± 1 SE
		12/7/2005 to 1/9/2007	
1	Control 0.5 dS/m	0.57 ± 0.01	0.66 ± 0.01
2	NaCl 1.0 dS/m	1.05 ± 0.01	1.67 ± 0.05
3	NaCl 3.0 dS/m	3.12 ± 0.03	4.52 ± 0.11
4	NaCl 4.5 dS/m	4.32 ± 0.05	5.71 ± 0.11
5	NaCl 6.0 dS/m	5.72 ± 0.08	7.08 ± 0.12
6	$CaCl_2$ 1.0 dS/m	1.06 ± 0.01	1.54 ± 0.02
7	$CaCl_2$ 3.0 dS/m	2.95 ± 0.02	5.08 ± 0.13
8	$CaCl_2$ 4.5 dS/m	4.52 ± 0.04	7.10 ± 0.16
9	$CaCl_2$ 6.0 dS/m	6.12 ± 0.04	8.83 ± 0.17
10	NaCl + $CaCl_2$ 1.0 dS/m	1.09 ± 0.01	1.61 ± 0.03
11	NaCl + $CaCl_2$ 3.0 dS/m	2.94 ± 0.03	4.60 ± 0.11
12	NaCl + $CaCl_2$ 4.5 dS/m	4.59 ± 0.03	6.83 ± 0.16
13	NaCl + $CaCl_2$ 6.0 dS/m	6.10 ± 0.04	8.40 ± 0.15
14	Na_2SO_4 1.0 dS/m	1.09 ± 0.01	1.73 ± 0.05
15	Na_2SO_4 3.0 dS/m	3.10 ± 0.04	4.68 ± 0.11
16	Na_2SO_4 4.5 dS/m	4.71 ± 0.01	6.08 ± 0.09
17	Na_2SO_4 6.0 dS/m	6.10 ± 0.02	7.37 ± 0.11

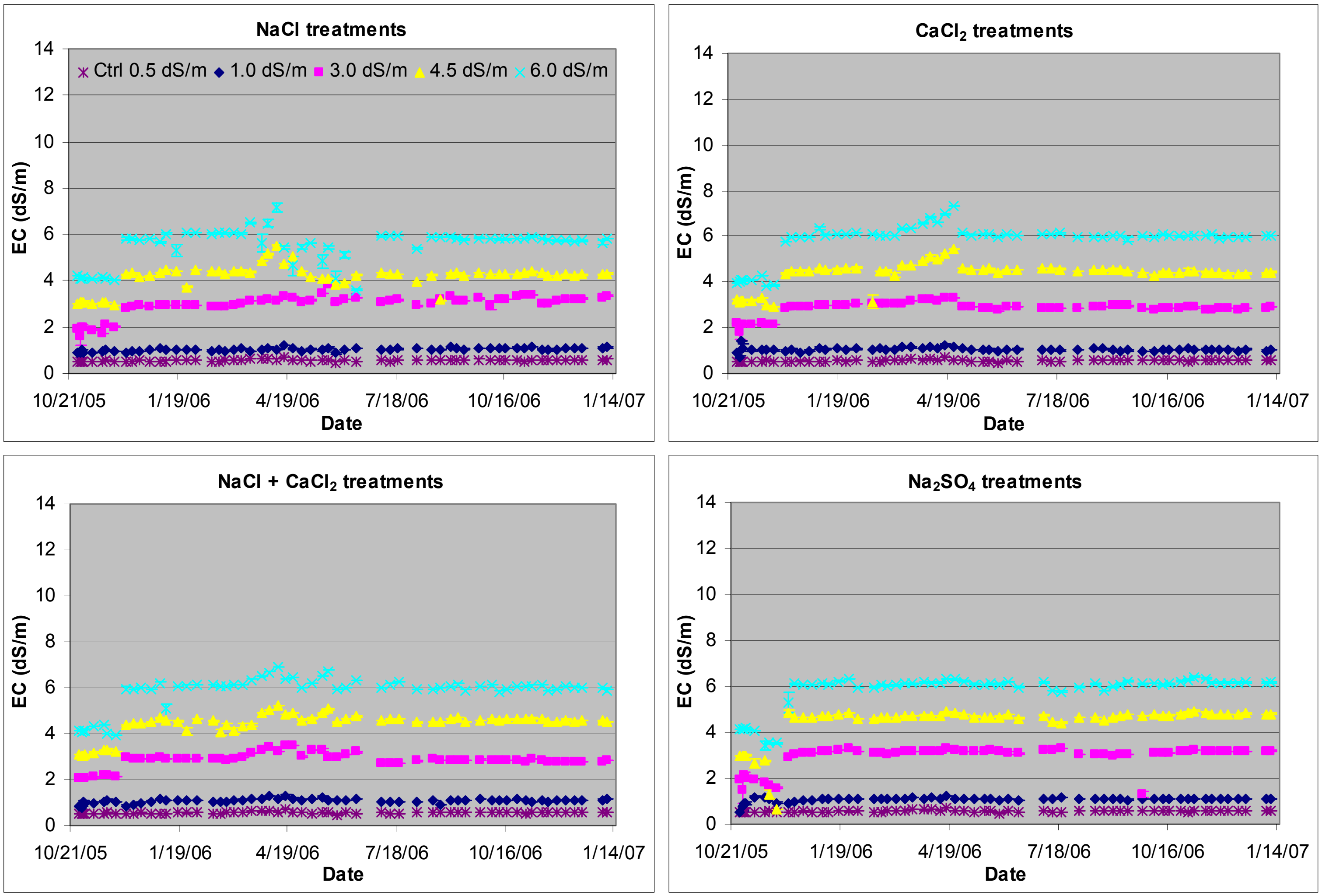

Figure 7. Mean EC (dS/m) by treatment over the experiment duration. Control treatment is repeated in each graph. Error bars indicate ± 1 SE.

Table 4. Treatment pH.

Trt. no.	Salinity type	EC (dS/m)*	pH
1	Control	0.5	5.3
2	NaCl	1.0	5.3
3		3.0	5.3
4		4.5	5.2
5		6.0	5.3
6	$CaCl_2 \cdot 2H_2O$	1.0	5.3
7		3.0	5.1
8		4.5	5.1
9		6.0	5.1
10	NaCl + $CaCl_2 \cdot 2H_2O$	1.0	5.3
11		3.0	5.3
12		4.5	5.3
13		6.0	5.3
14	Na_2SO_4	1.0	5.4
15		3.0	5.5
16		4.5	5.4
17		6.0	5.4

*EC for treatments 2-17 includes 0.5 dS/m Hoagland's solution

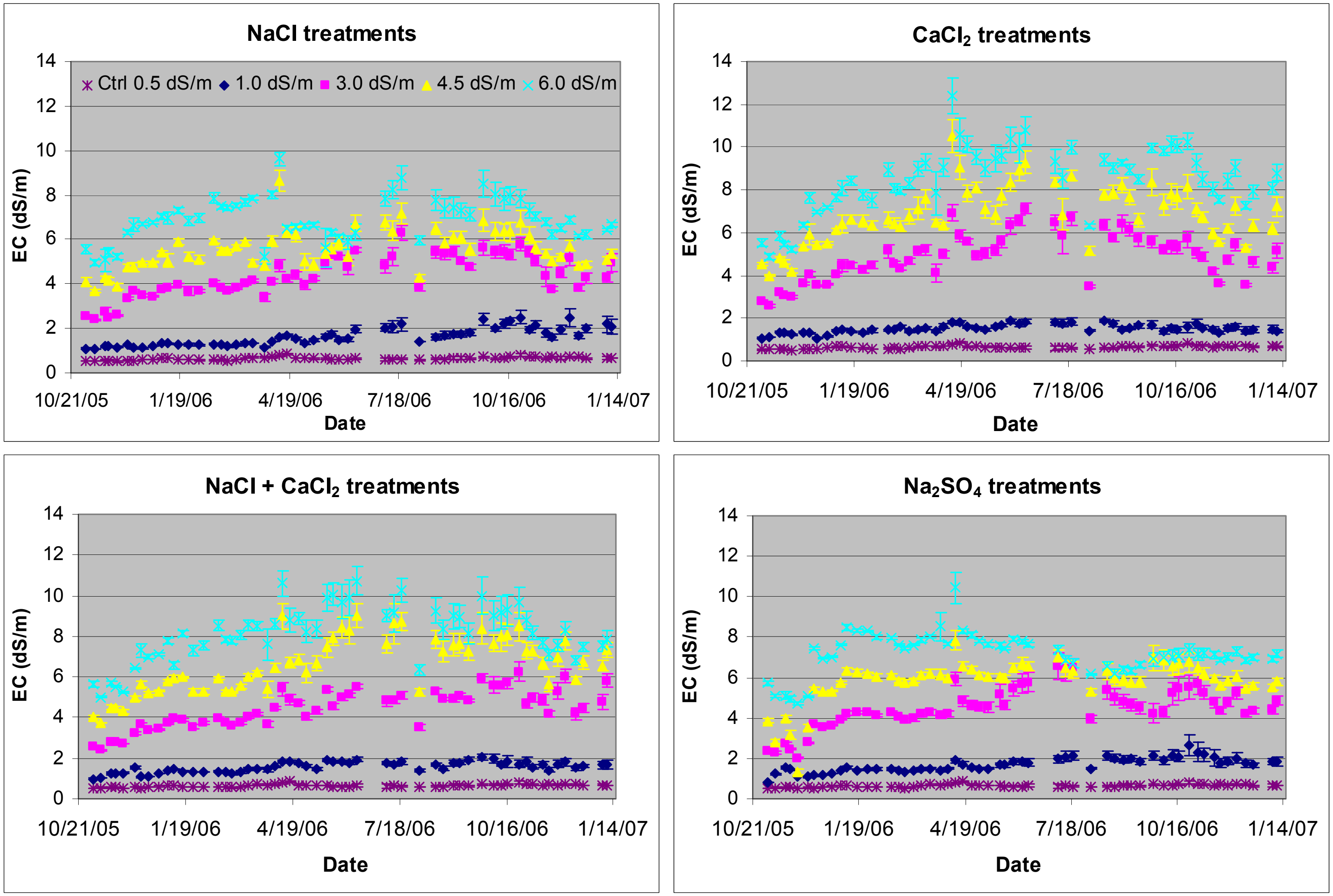

Figure 8. Mean leachate EC (dS/m) by treatment over the experiment duration. Control treatment is repeated in each graph. Error bars indicate ± 1 SE.

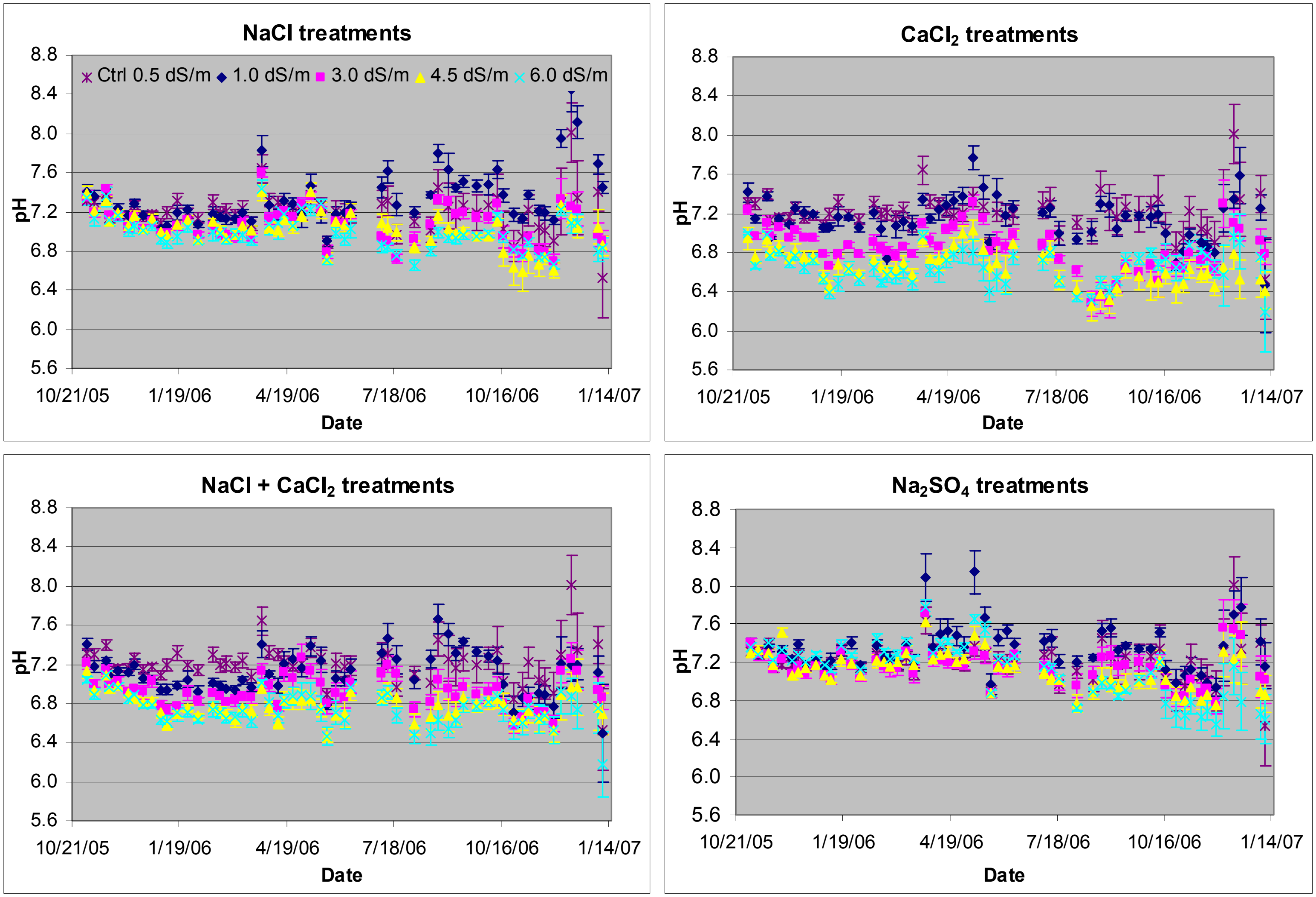

Figure 9. Mean leachate pH by treatment over the experiment duration. Control treatment is repeated in each graph. Error bars indicate ± 1 SE.

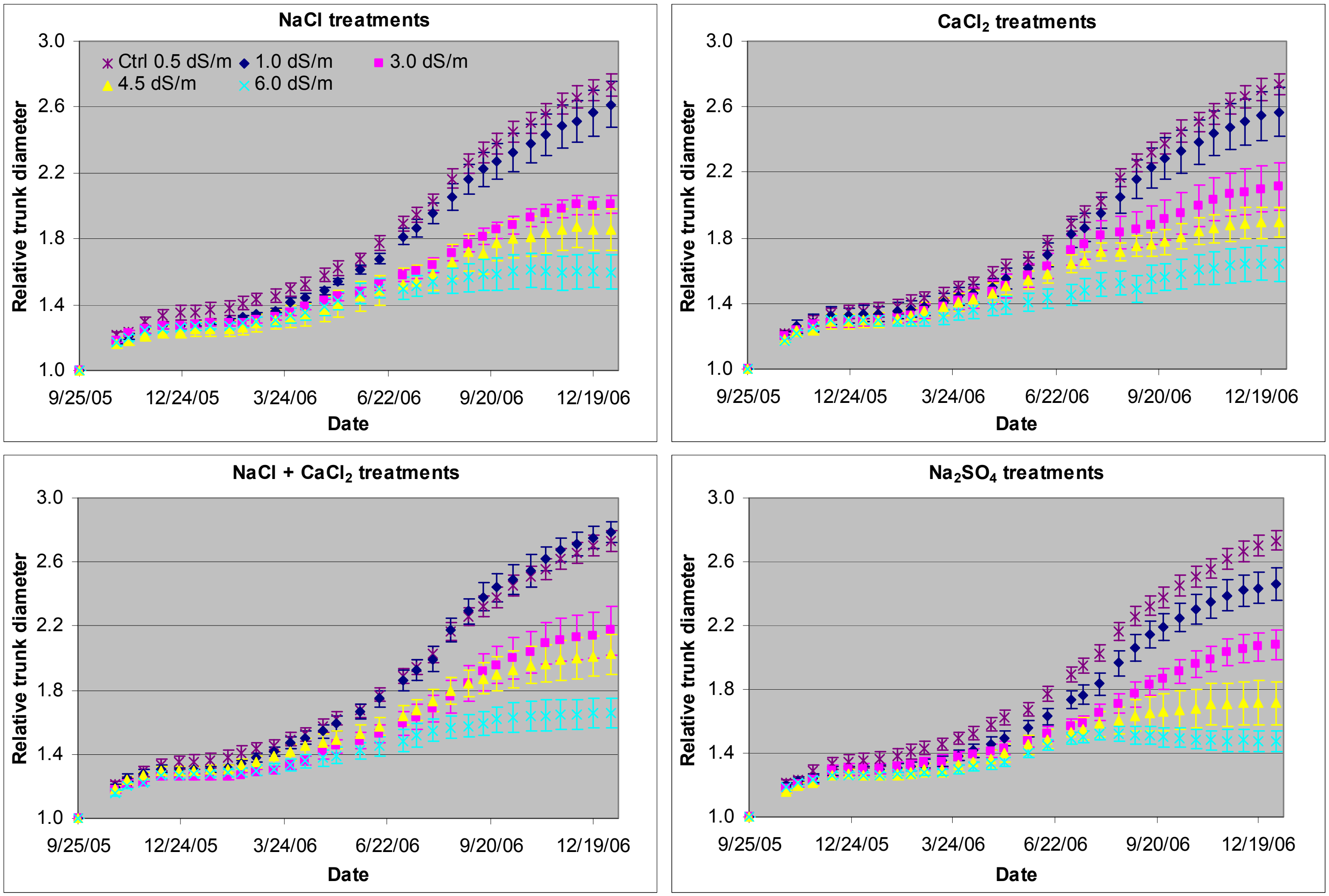

Figure 10. Relative trunk diameter by treatment over the experiment duration. Values were calculated by dividing each measurement for a replicate and date by the measurement from the same replicate on 9/25/05. Replicate values were then averaged within each treatment by date. Control treatment is repeated in each graph. Error bars indicate ± 1 SE.

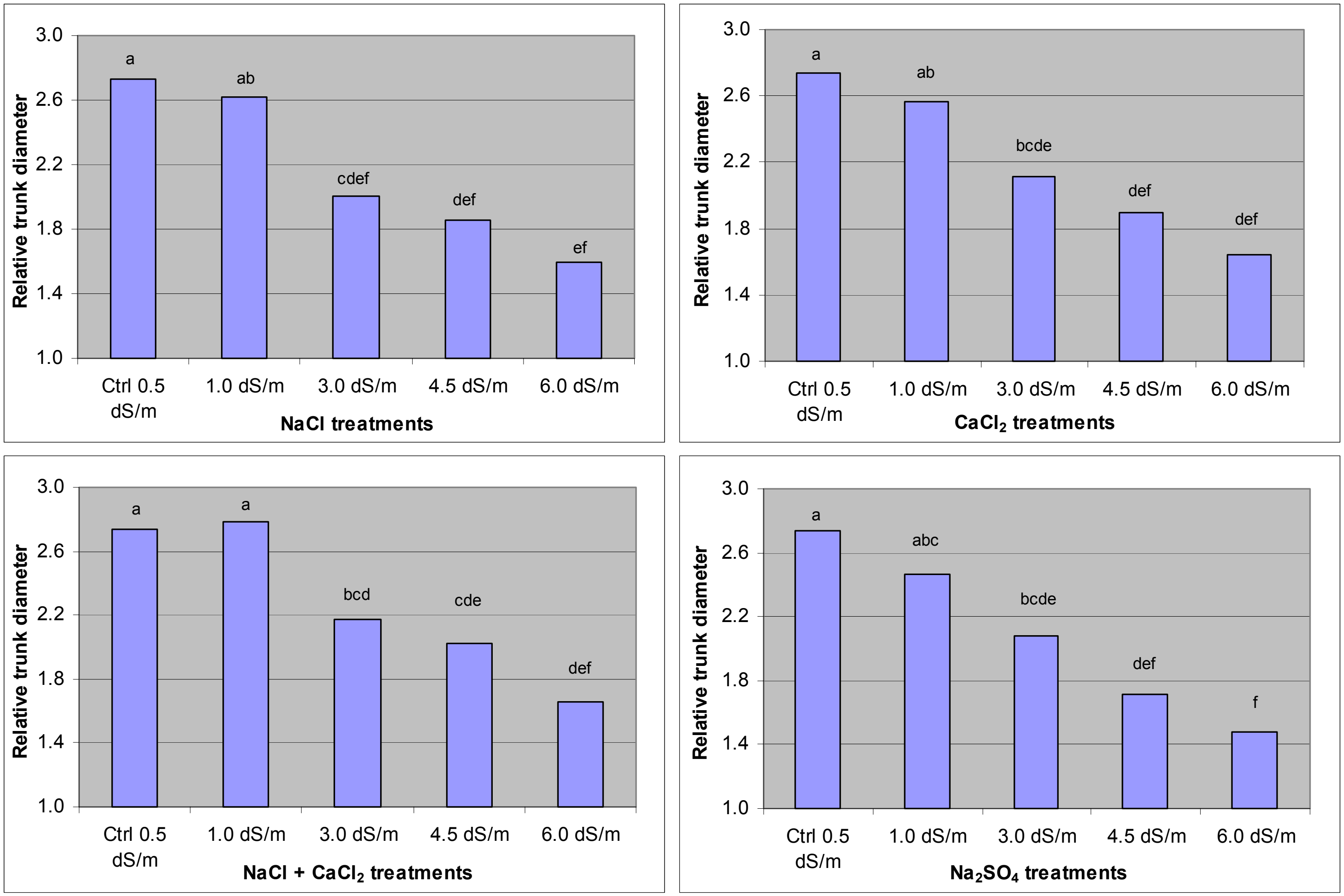

Figure 11. Relative trunk diameter by treatment. Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Replicate values were then averaged within each treatment. Control treatment is repeated in each graph. Tukey-Kramer mean separation analysis performed among all 17 treatments. Bars with like letters indicate lack of significance, $\alpha = 0.05$.

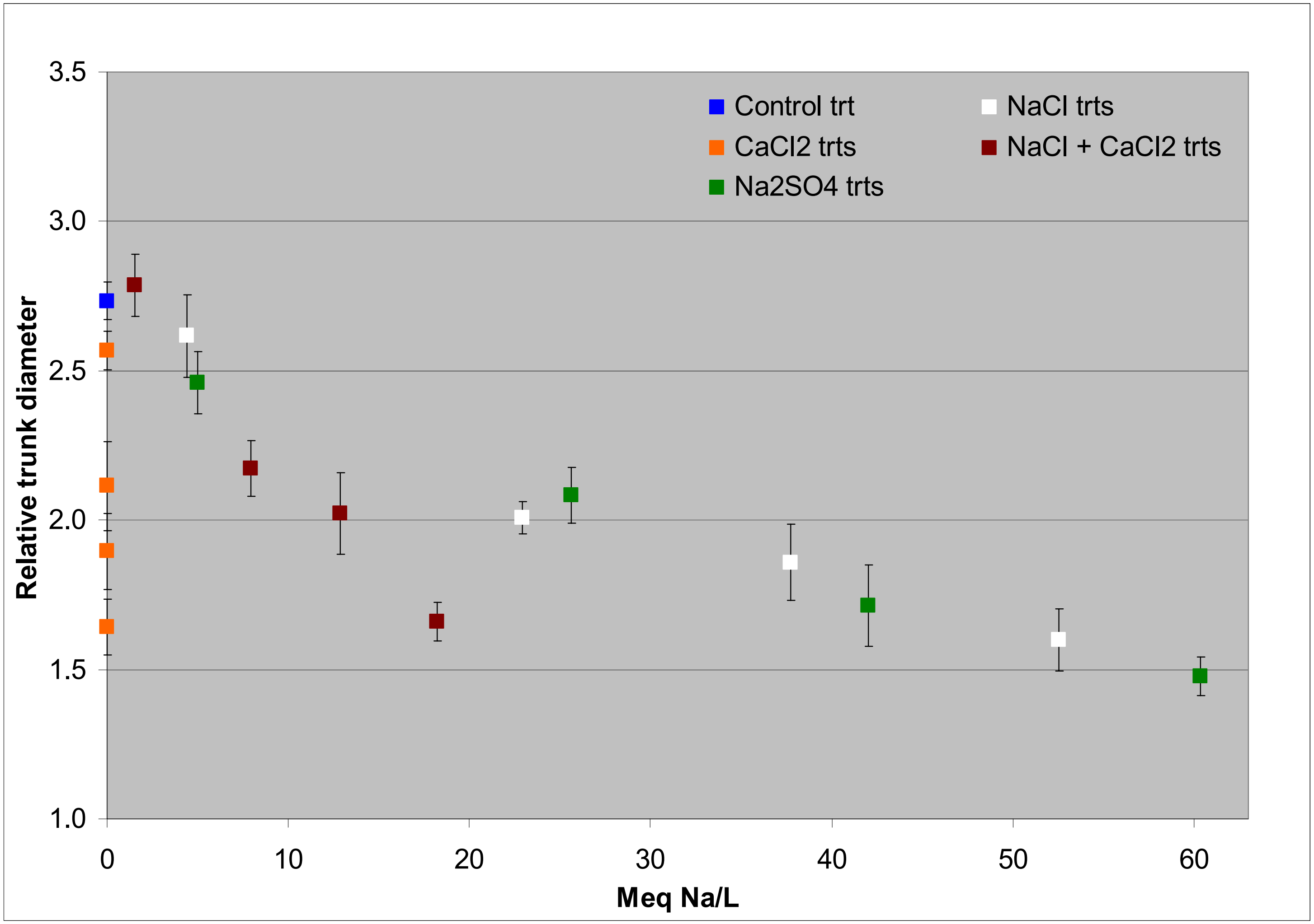

Figure 12. Relative trunk diameter as a function of meq Na/L for each irrigation treatment. An increase in meq Na/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Replicate values were then averaged within each treatment. Error bars indicate ± 1 SE.

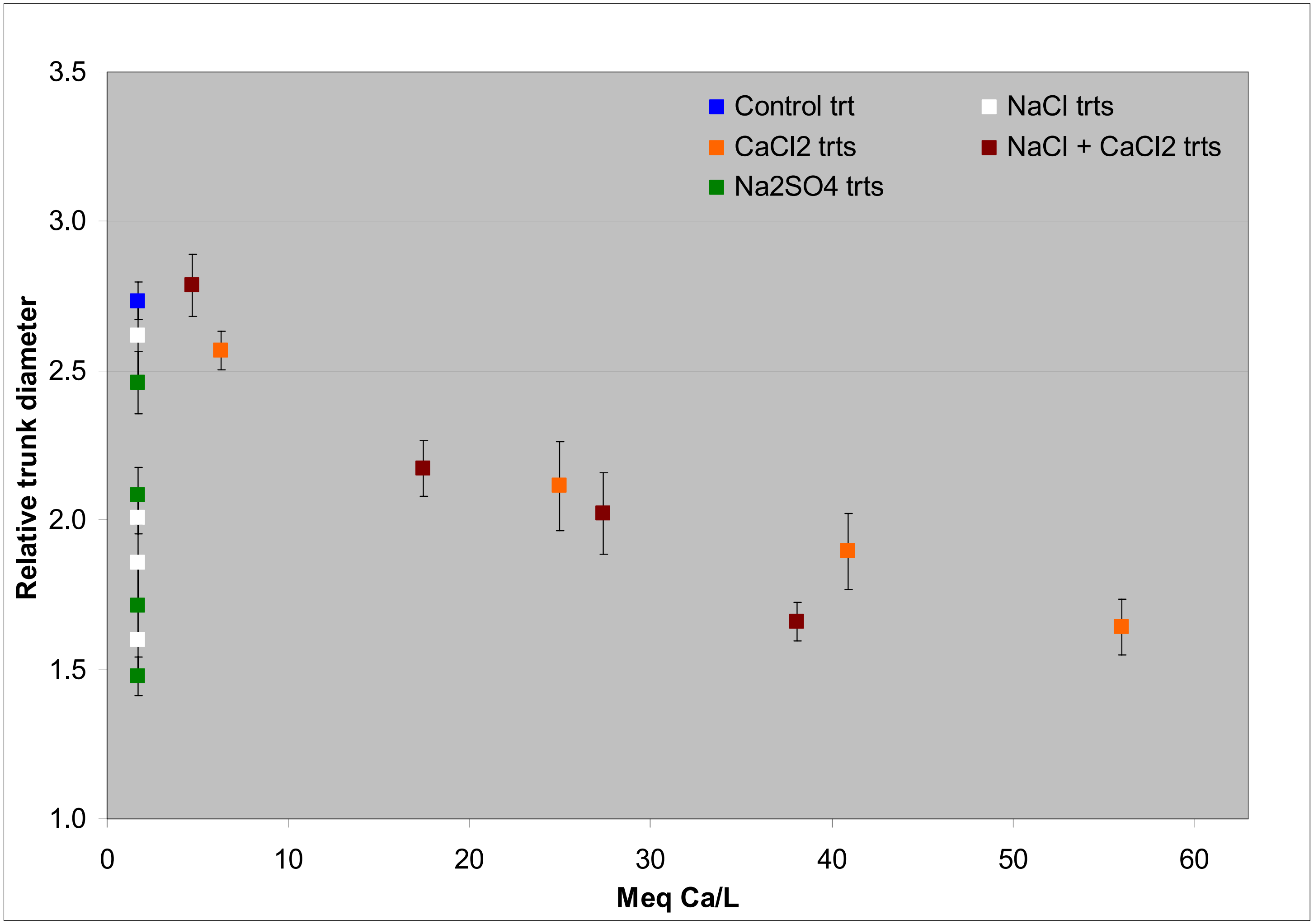

Figure 13. Relative trunk diameter as a function of meq Ca/L for each irrigation treatment. An increase in meq Ca/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Replicate values were then averaged within each treatment. Error bars indicate ± 1 SE.

Table 5. Mean relative trunk diameter and tree height by treatment. Values are the mean of six replicates (9 replicates for the control) and were calculated by dividing the final measurement for given tree by the initial measurement. ANOVA α = 0.05.

Treatment	Mean Relative Trunk Diameter ± 1 SE 9/25/2005 to 1/3/2007	Mean Relative Height ± 1 SE 9/15/2005 to 1/8/2007
Control 0.5 dS/m	2.73 ± 0.06	2.41 ± 0.22
NaCl 1.0 dS/m	2.62 ± 0.14	2.14 ± 0.23
NaCl 3.0 dS/m	2.01 ± 0.05	1.60 ± 0.13
NaCl 4.5 dS/m	1.86 ± 0.13	1.50 ± 0.13
NaCl 6.0 dS/m	1.60 ± 0.10	1.46 ± 0.17
$CaCl_2$ 1.0 dS/m	2.57 ± 0.15	2.10 ± 0.23
$CaCl_2$ 3.0 dS/m	2.11 ± 0.14	2.09 ± 0.12
$CaCl_2$ 4.5 dS/m	1.90 ± 0.09	2.05 ± 0.18
$CaCl_2$ 6.0 dS/m	1.64 ± 0.10	1.56 ± 0.10
NaCl + $CaCl_2$ 1.0 dS/m	2.79 ± 0.06	2.02 ± 0.30
NaCl + $CaCl_2$ 3.0 dS/m	2.17 ± 0.15	1.70 ± 0.27
NaCl + $CaCl_2$ 4.5 dS/m	2.02 ± 0.13	1.56 ± 0.12
NaCl + $CaCl_2$ 6.0 dS/m	1.66 ± 0.09	1.70 ± 0.15
Na_2SO_4 1.0 dS/m	2.46 ± 0.10	2.17 ± 0.23
Na_2SO_4 3.0 dS/m	2.08 ± 0.09	2.07 ± 0.26
Na_2SO_4 4.5 dS/m	1.71 ± 0.14	1.60 ± 0.15
Na_2SO_4 6.0 dS/m	1.48 ± 0.07	1.43 ± 0.12
ANOVA		
Block	F = 6.36, P = 0.0139	F = 2.91, P = 0.0924
Trt	F = 16.47, P < 0.0001	F = 2.32, P = 0.0083

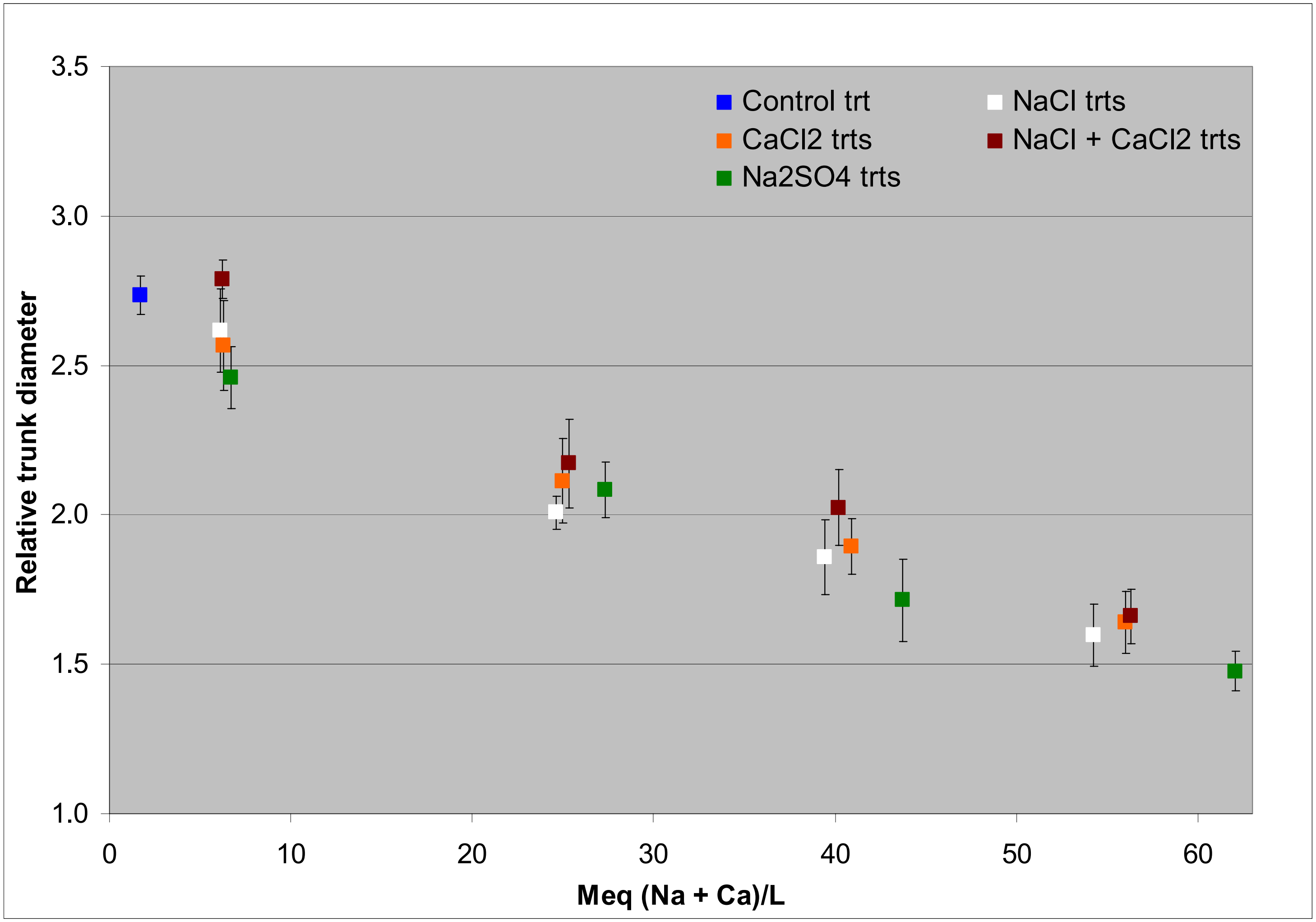

Figure 14. Relative trunk diameter as a function of meq (Na + Ca)/L for each irrigation treatment. An increase in meq Na + Ca/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Replicate values were then averaged within each treatment. Error bars indicate ± 1 SE.

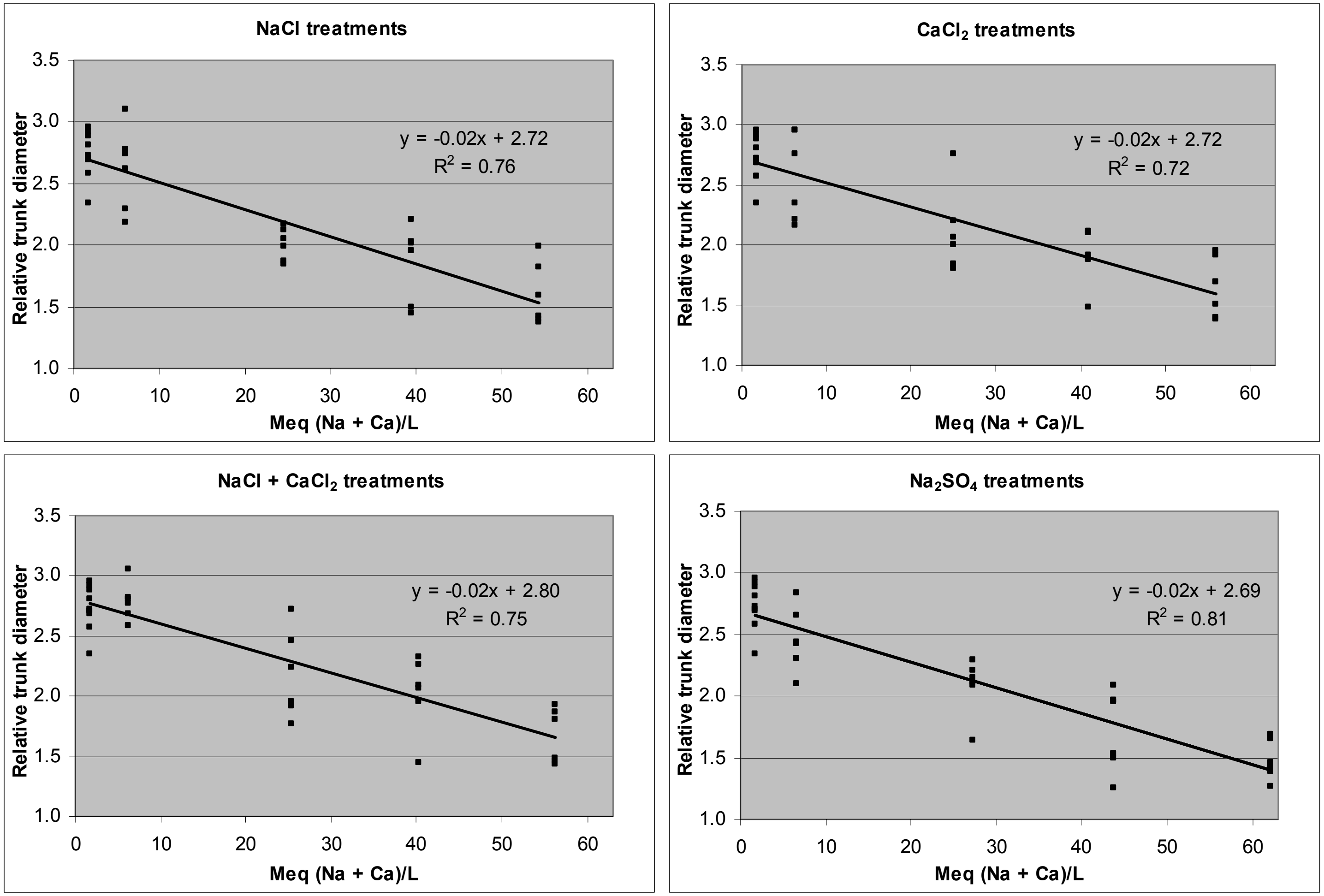

Figure 15. Relative trunk diameter as a function of meq (Na + Ca)/L for each replicate by irrigation treatment. An increase in meq (Na + Ca)/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Control treatment values are the leftmost vertical group of points and are repeated in each graph.

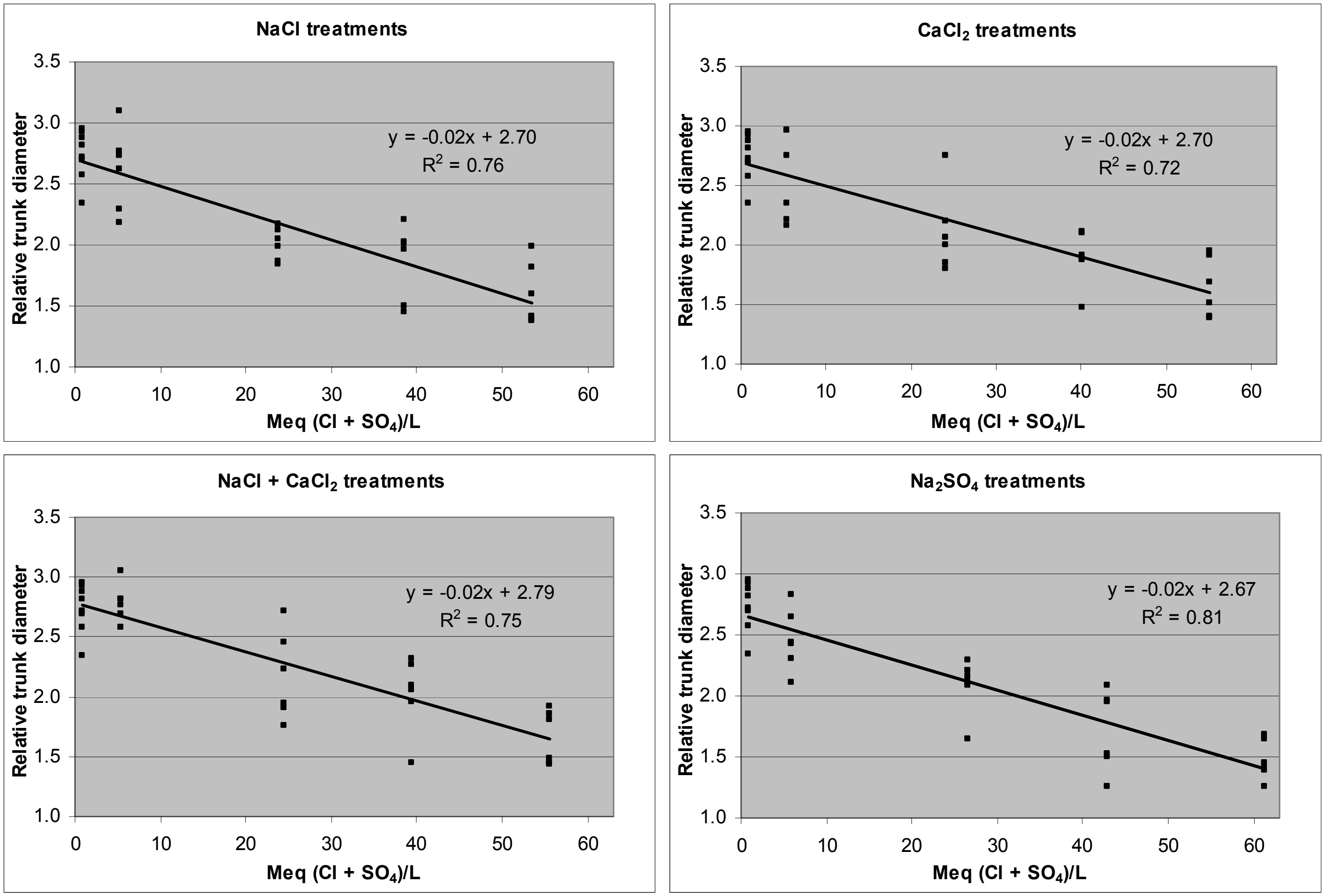

Figure 16. Relative trunk diameter as a function of meq (Cl + SO_4)/L for each replicate by irrigation treatment. An increase in meq (Cl + SO_4)/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/3/07 by the measurement from the same replicate on 9/25/05. Control treatment values are the leftmost vertical group of points and are repeated in each graph.

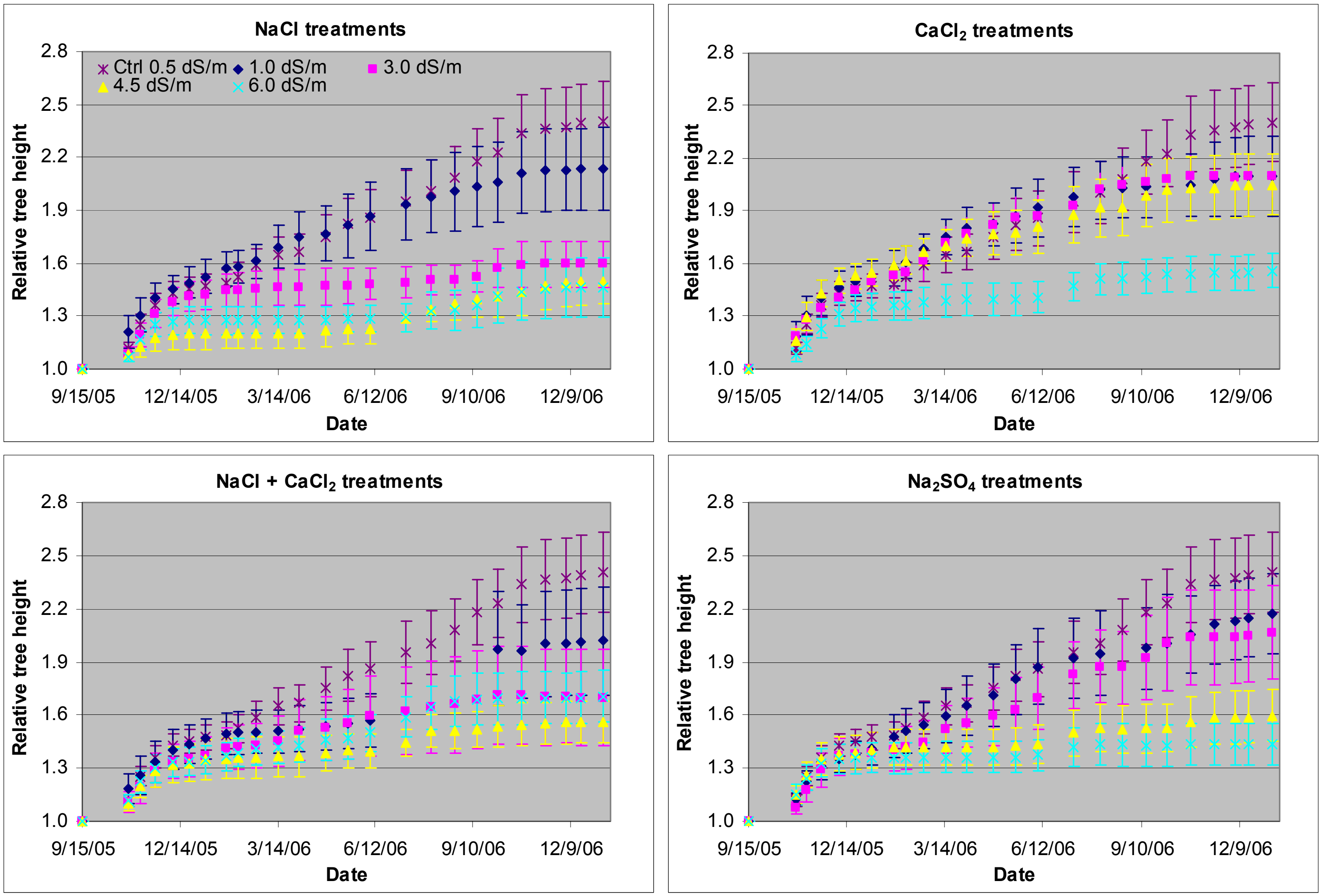

Figure 17. Relative tree height by treatment over the experiment duration. Values were calculated by dividing each measurement for a replicate and date by the measurement from the same replicate on 9/15/05. Replicate values were then averaged within each treatment by date. Control treatment is repeated in each graph. Error bars indicate ± 1 SE.

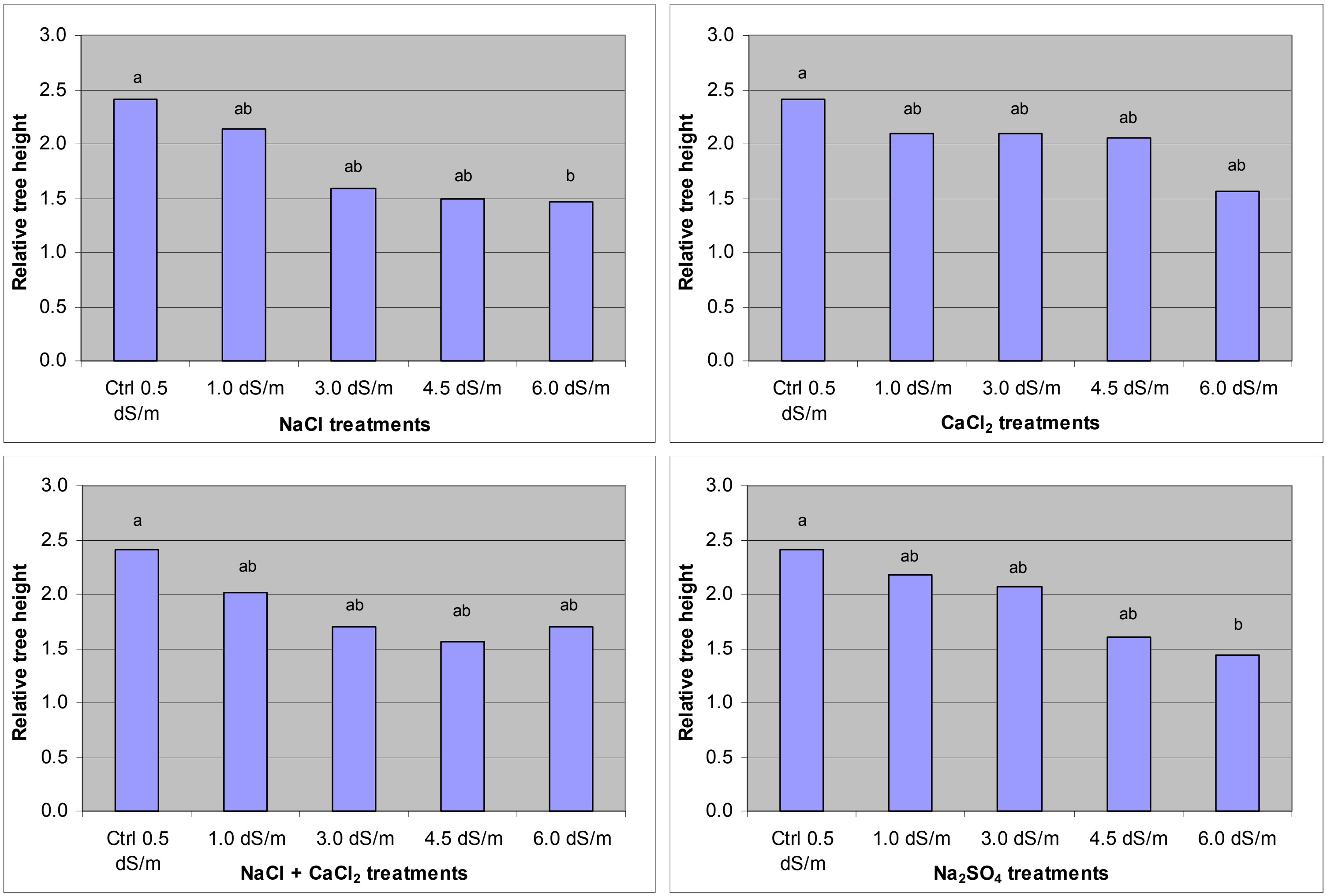

Figure 18. Relative tree height by treatment. Values were calculated by dividing each measurement for a replicate on 1/8/07 by the measurement from the same replicate on 9/15/05. Replicate values were then averaged within each treatment. Control treatment is repeated in each graph. Tukey-Kramer mean separation analysis performed among all 17 treatments. Bars with like letters indicate lack of significance, $\alpha = 0.05$.

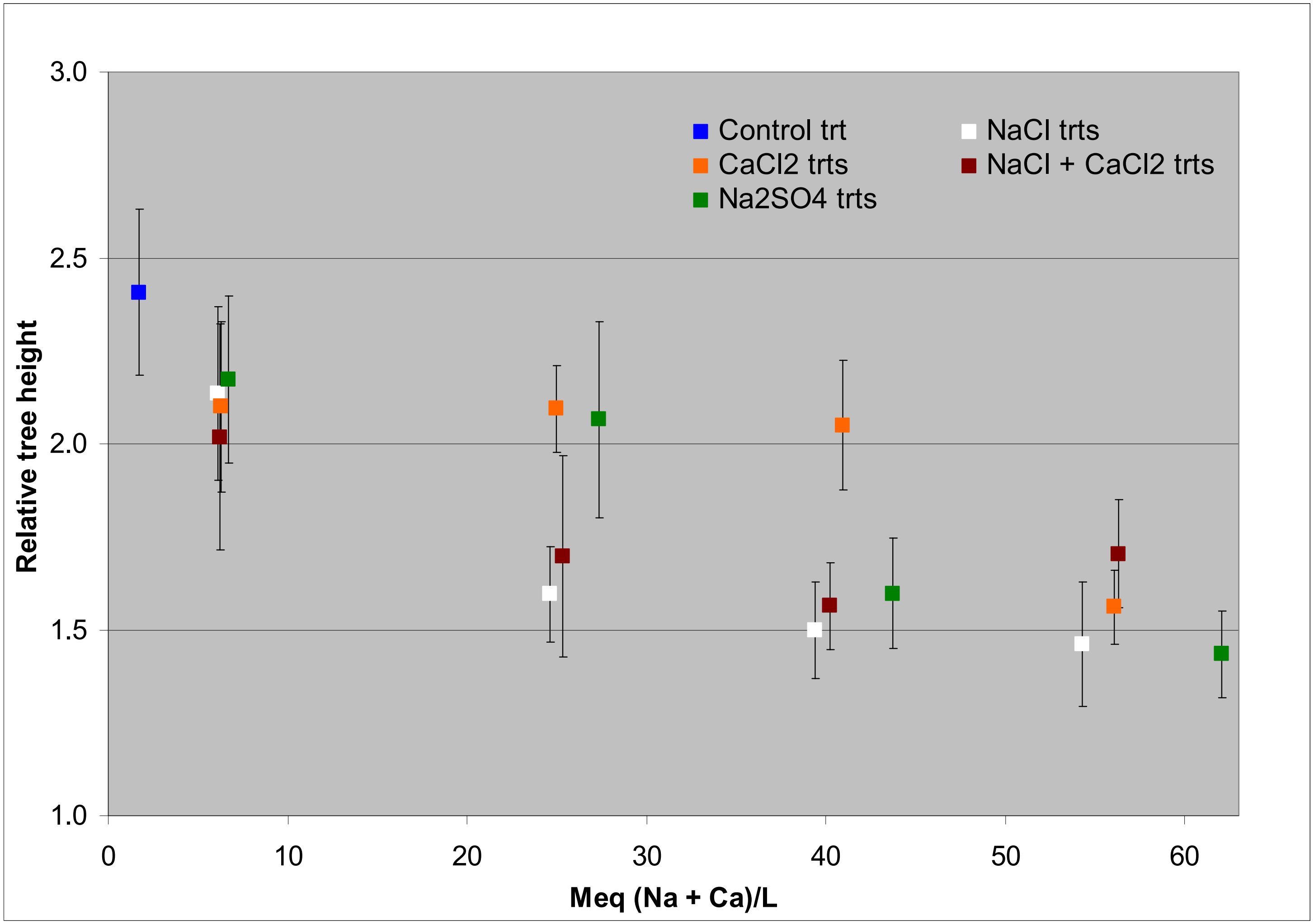

Figure 19. Relative tree height as a function of meq (Na + Ca)/L for each irrigation treatment. An increase in meq (Na + Ca)/L or decrease in relative trunk diameter within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/8/07 by the measurement from the same replicate on 9/15/05. Replicate values were then averaged within each treatment. Error bars indicate ± 1 SE.

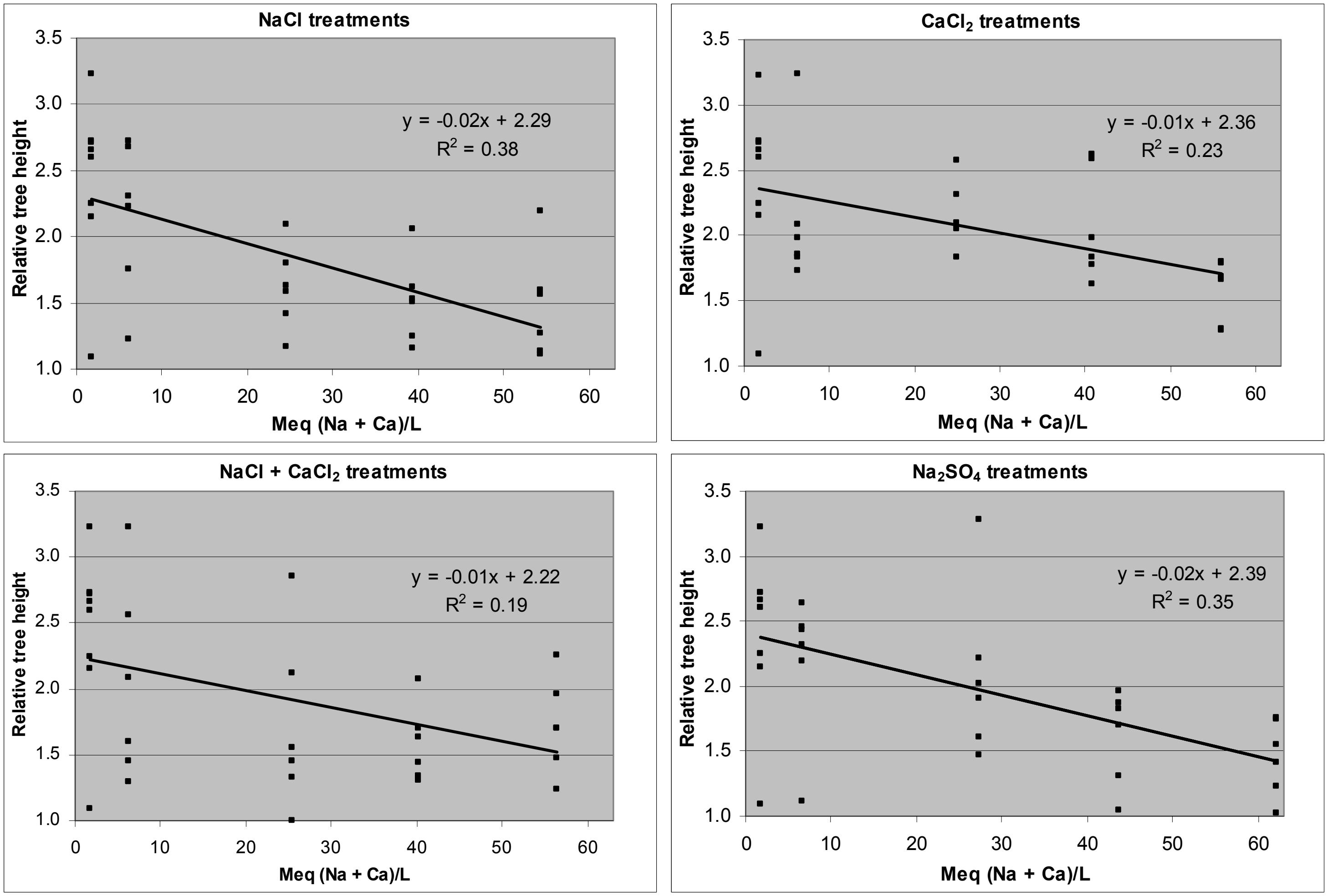

Figure 20. Relative tree height as a function of meq (Na + Ca)/L for each replicate by irrigation treatment. An increase in meq (Na + Ca)/L or decrease in relative tree height within a salinity type corresponds to an increase in the treatment EC (1.0, 3.0, 4.5, 6.0 dS/m). Values were calculated by dividing each measurement for a replicate on 1/8/07 by the measurement from the same replicate on 9/15/05. Control treatment values are the leftmost vertical group of points and are repeated in each graph.

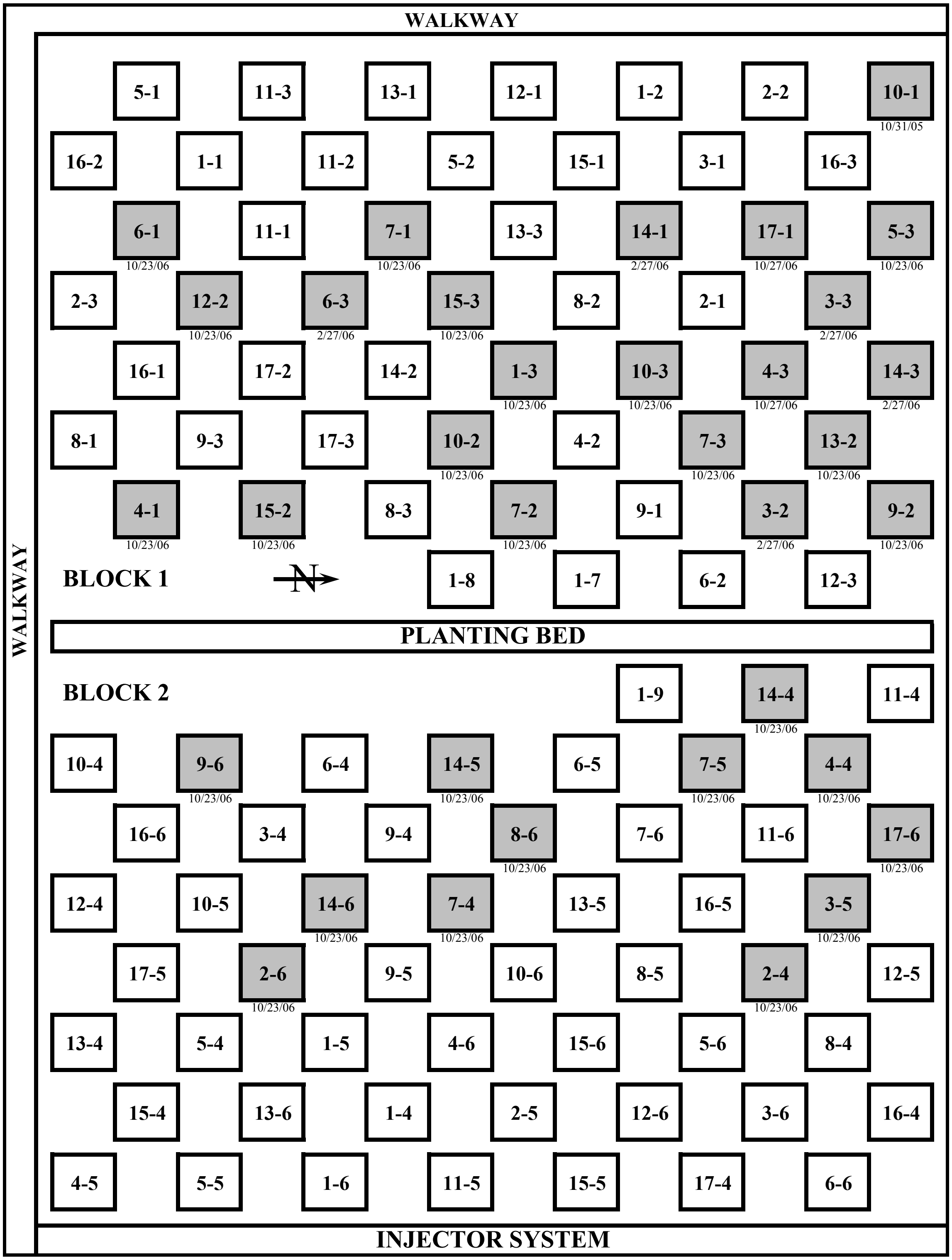

Figure 21. Trees moved in greenhouse. Affected trees are indicated as gray squares, with the exchange date listed below the square.

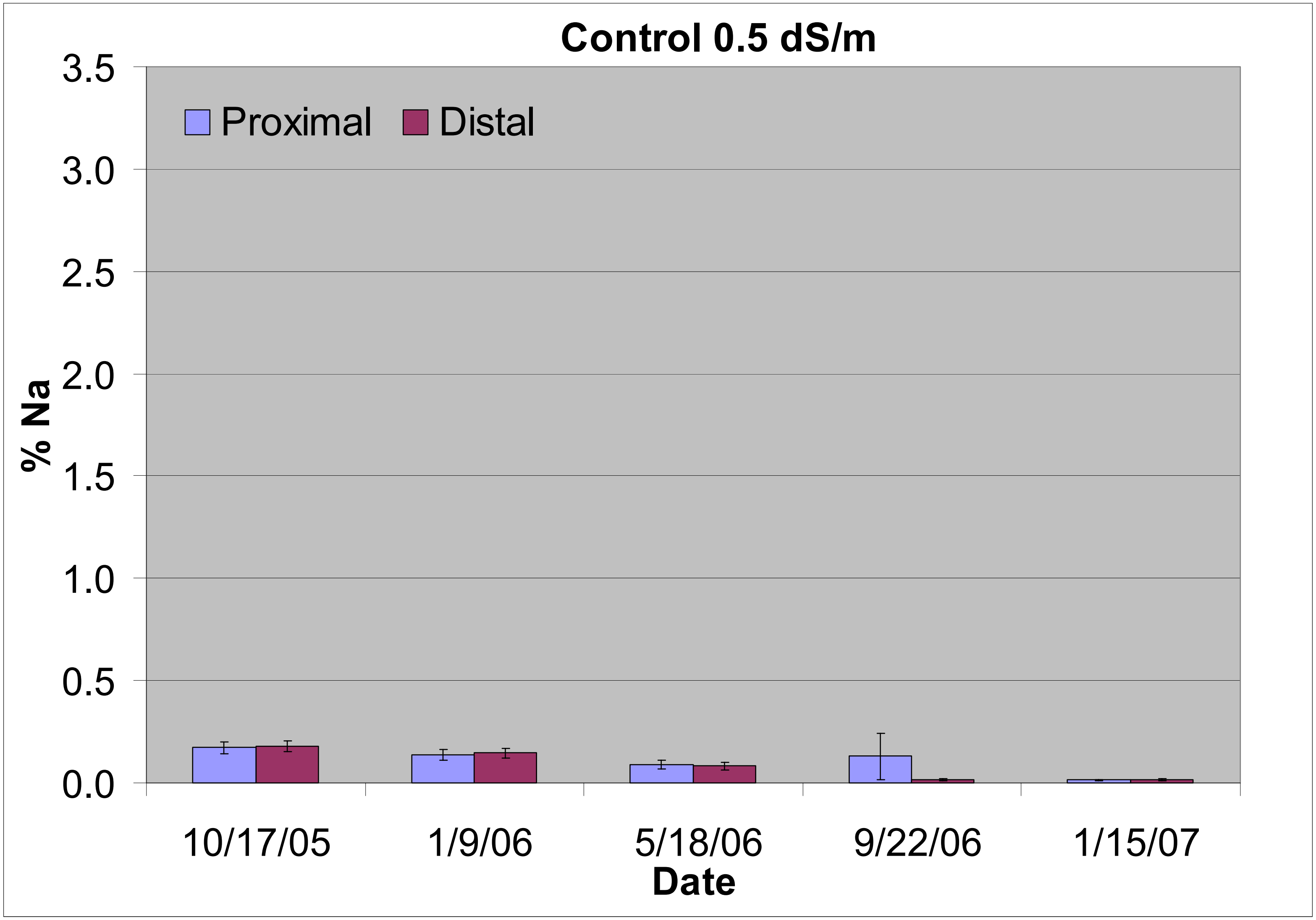

Figure 22. Leaf tissue mean % Na by section for the control treatment across five sampling dates. Error bars indicate ± 1 SE.

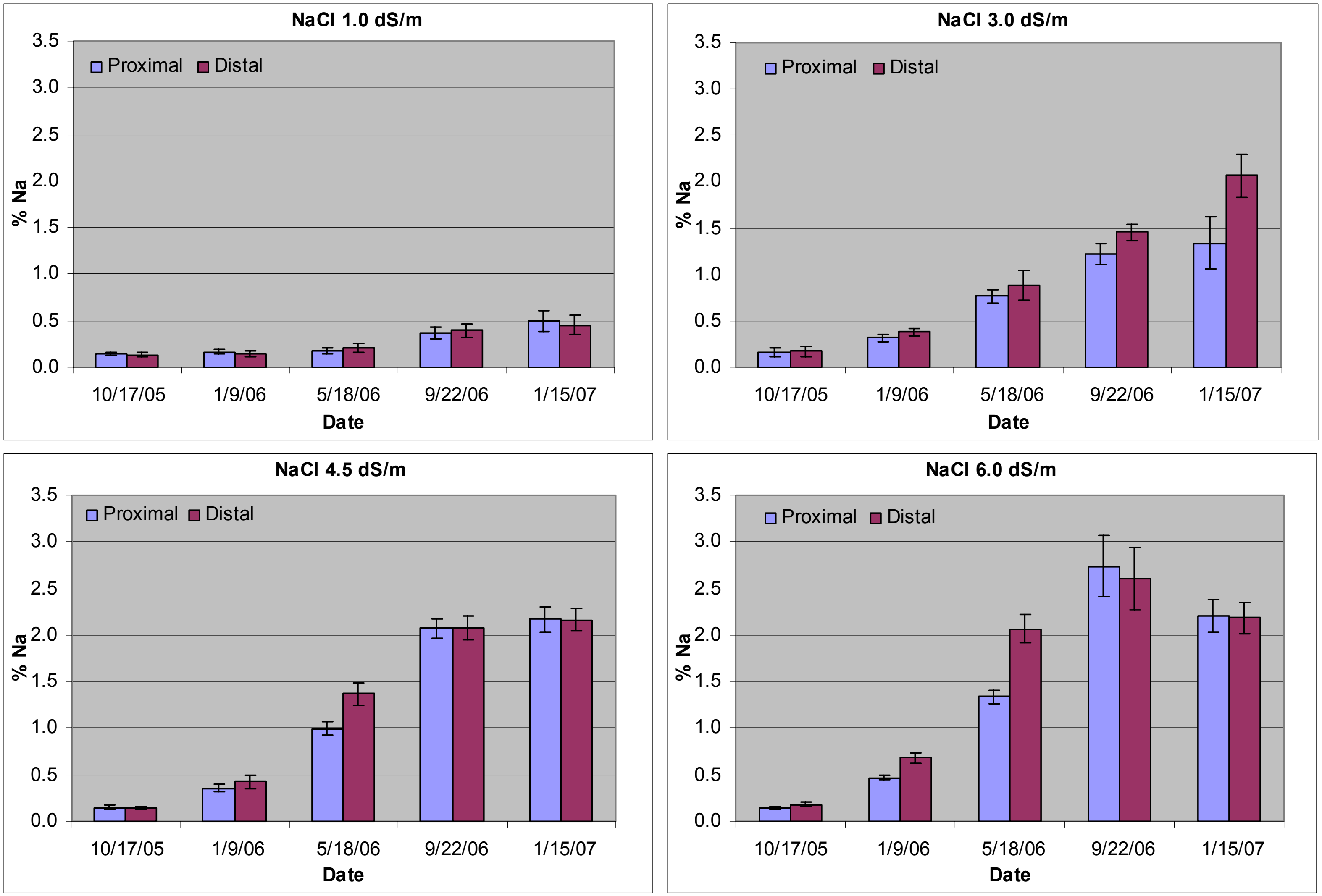

Figure 23. Leaf tissue mean % Na by section for the NaCl treatments across five sampling dates. Error bars indicate ± 1 SE.

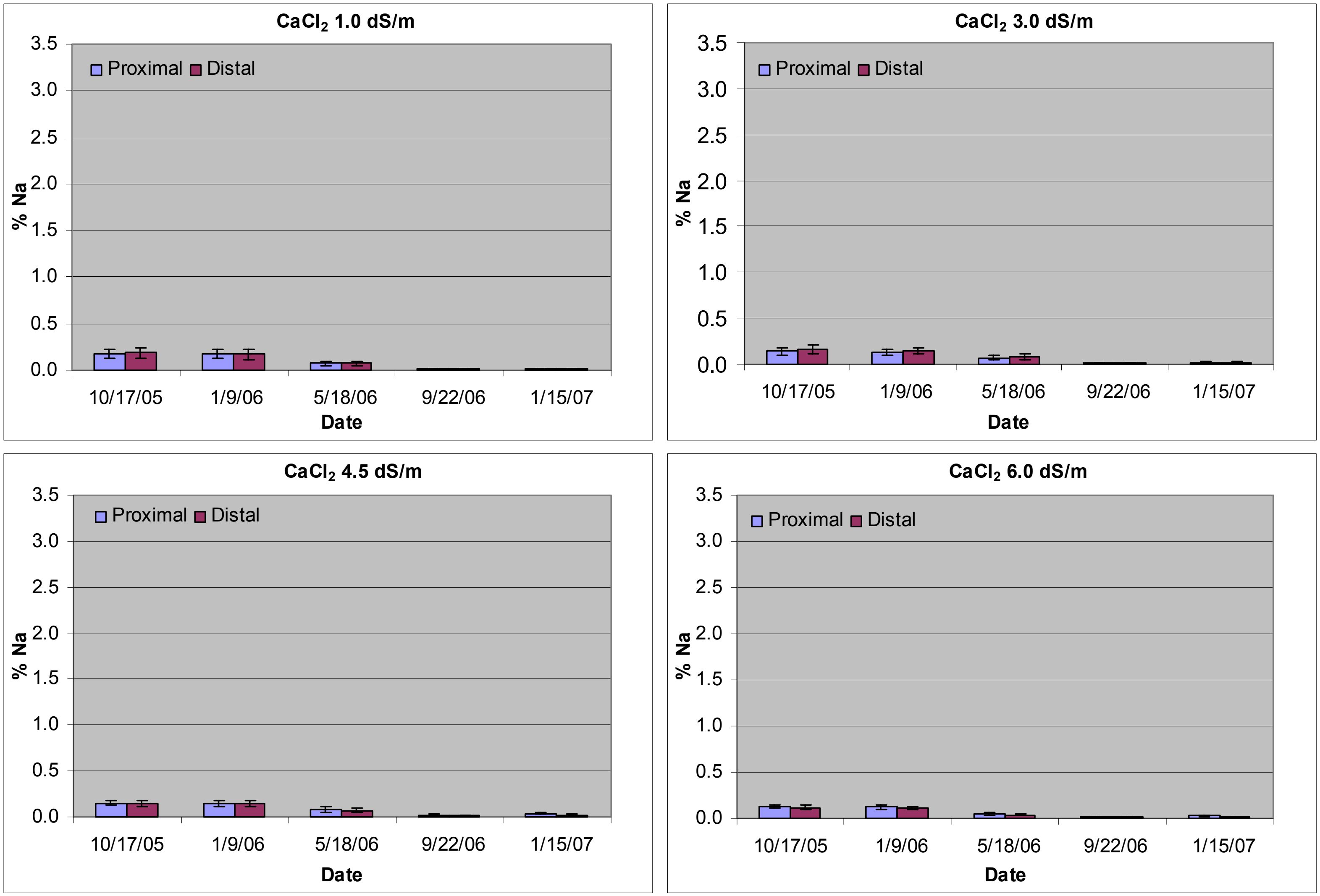

Figure 24. Leaf tissue mean % Na by section for the $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

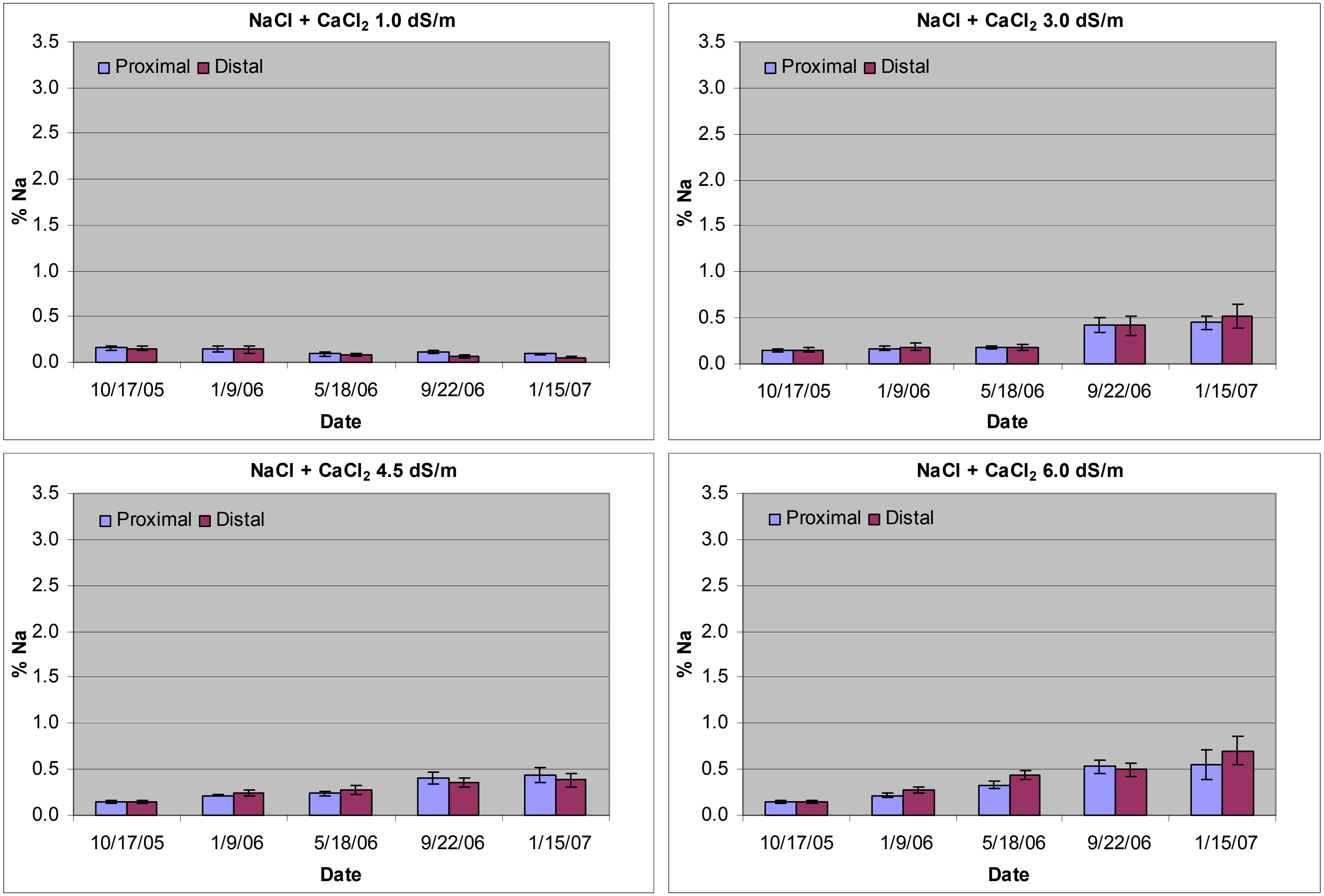

Figure 25. Leaf tissue mean % Na by section for the NaCl + $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

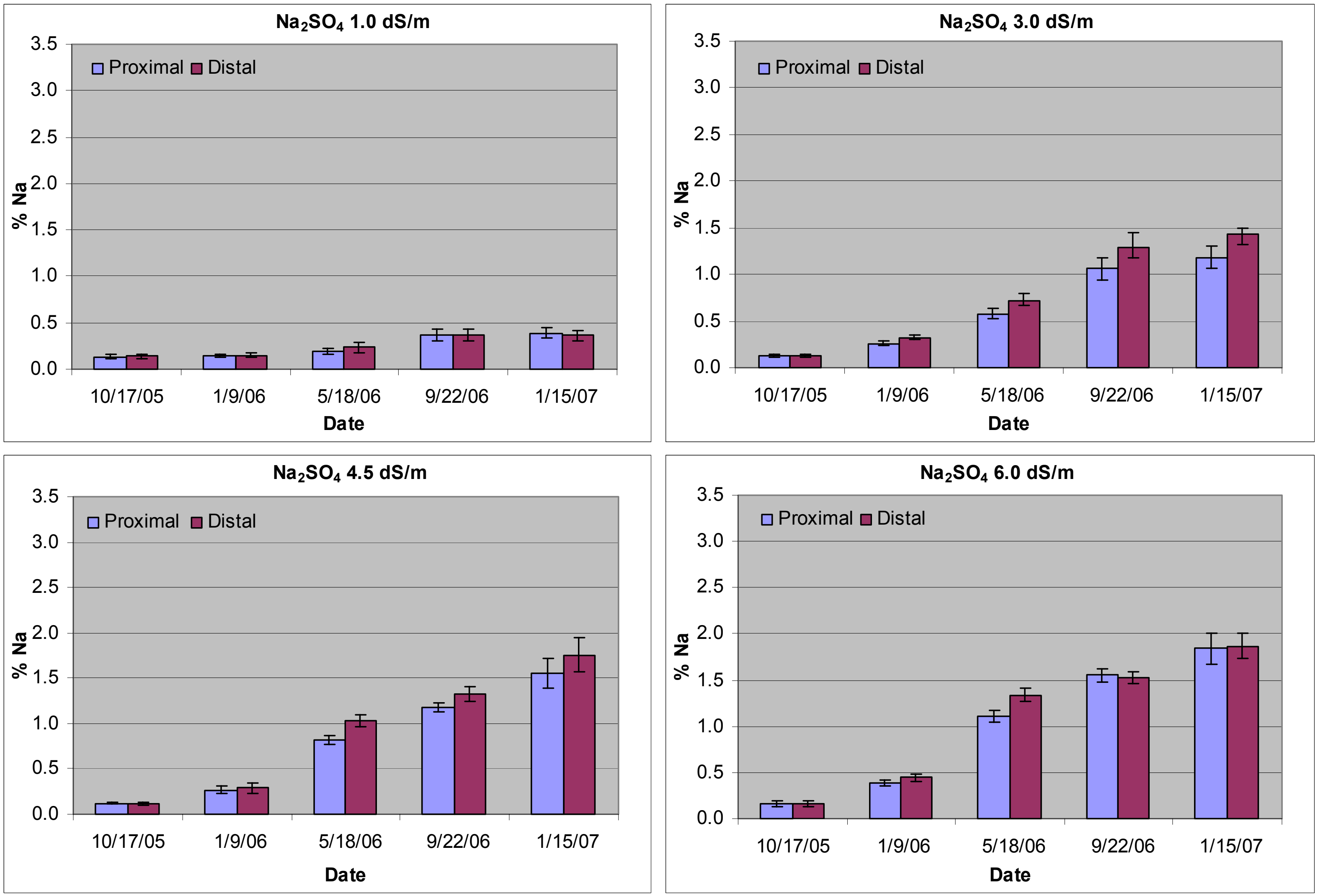

Figure 26. Leaf tissue mean % Na by section for the Na_2SO_4 treatments across five sampling dates. Error bars indicate ± 1 SE.

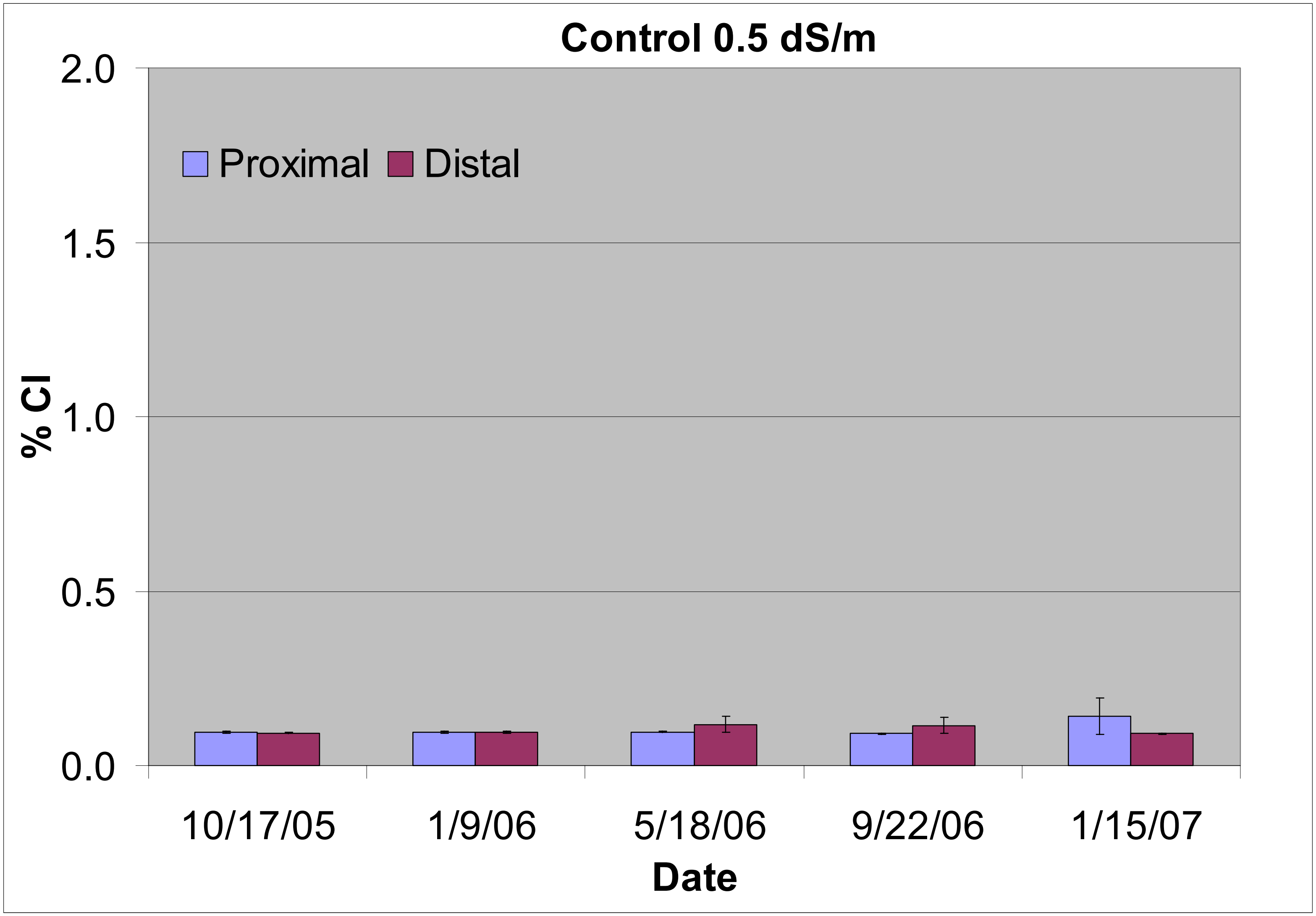

Figure 27. Leaf tissue mean % Cl by section for the control treatment across five sampling dates. Error bars indicate ± 1 SE.

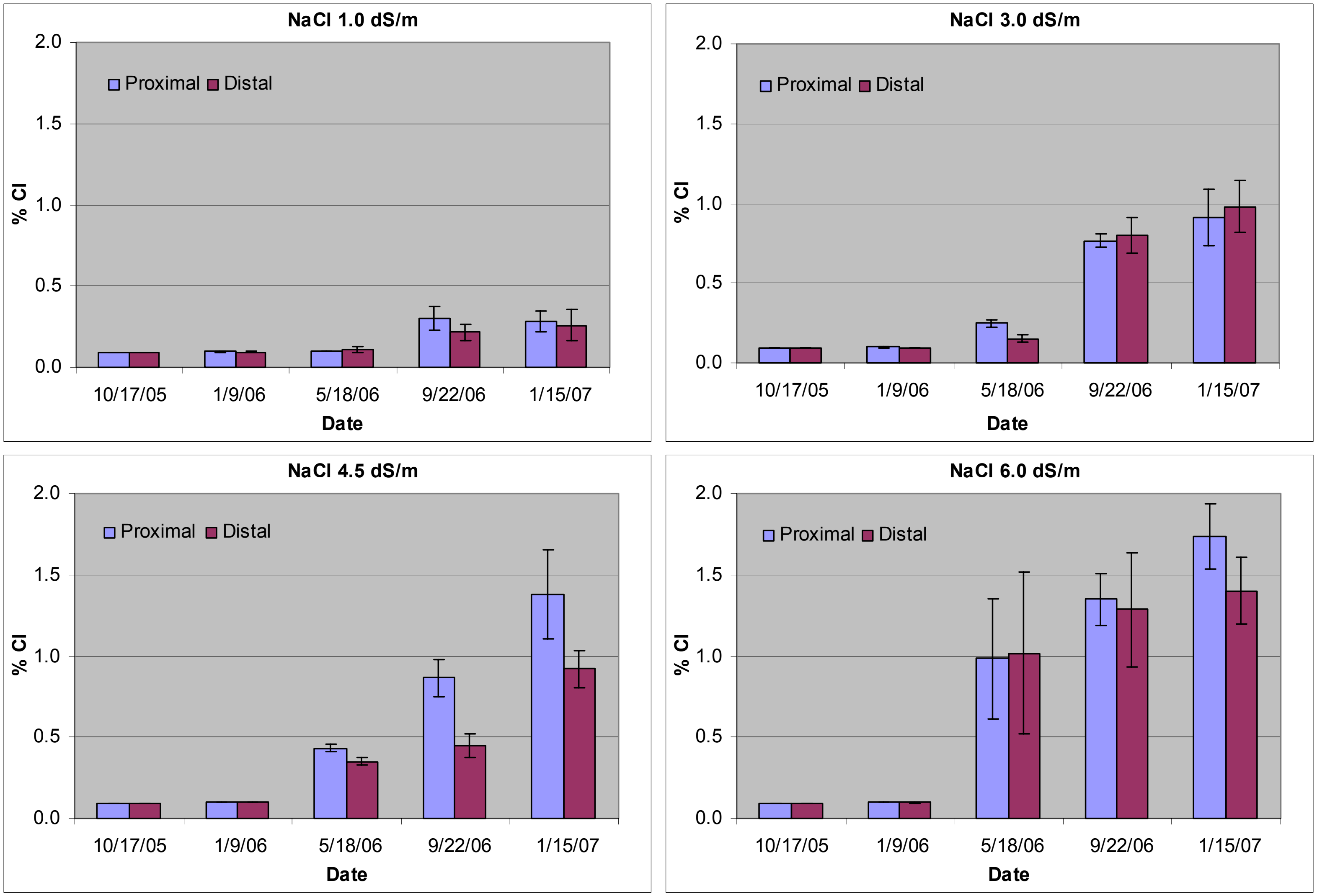

Figure 28. Leaf tissue mean % Cl by section for the NaCl treatments across five sampling dates. Error bars indicate ± 1 SE.

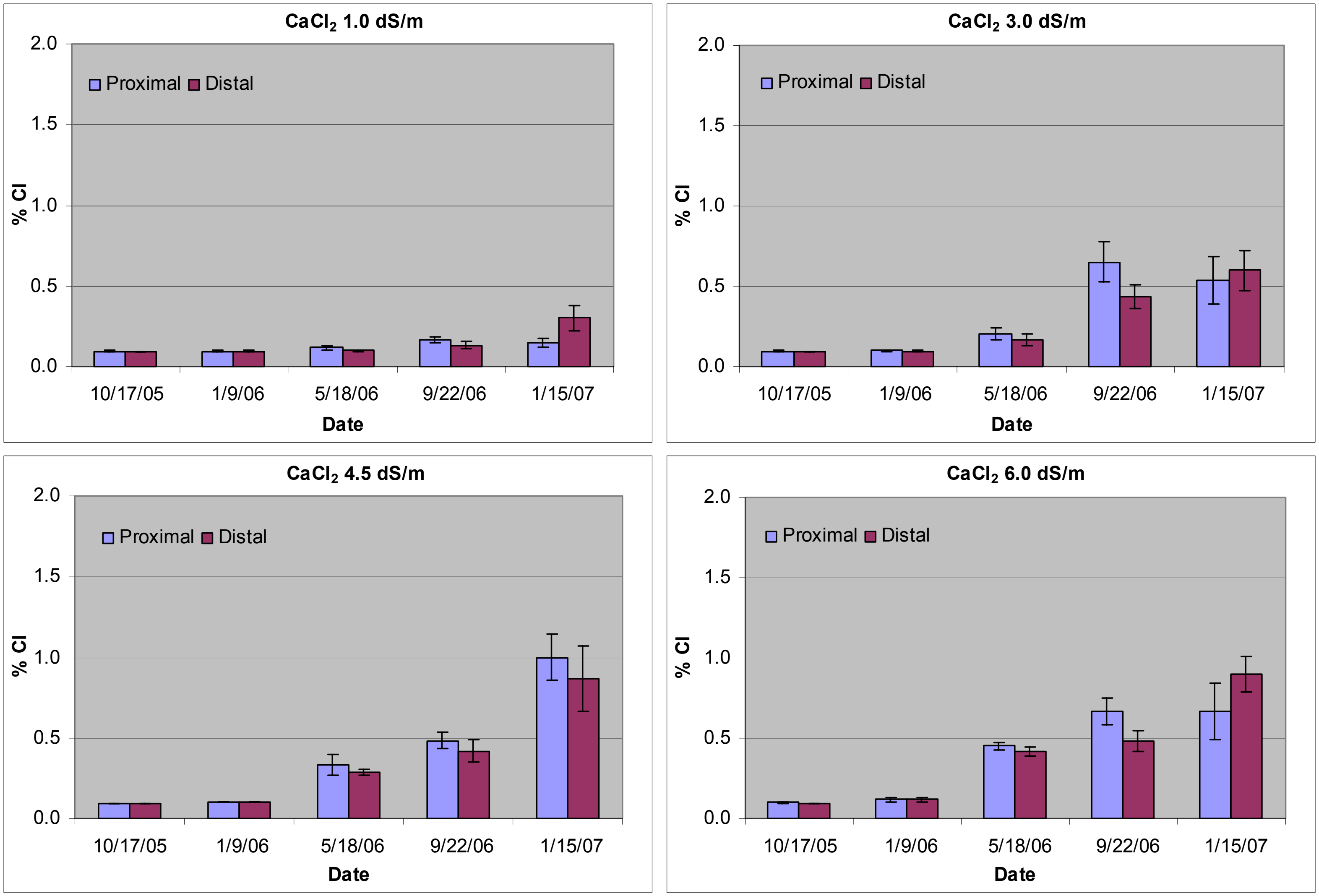

Figure 29. Leaf tissue mean % Cl by section for the $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

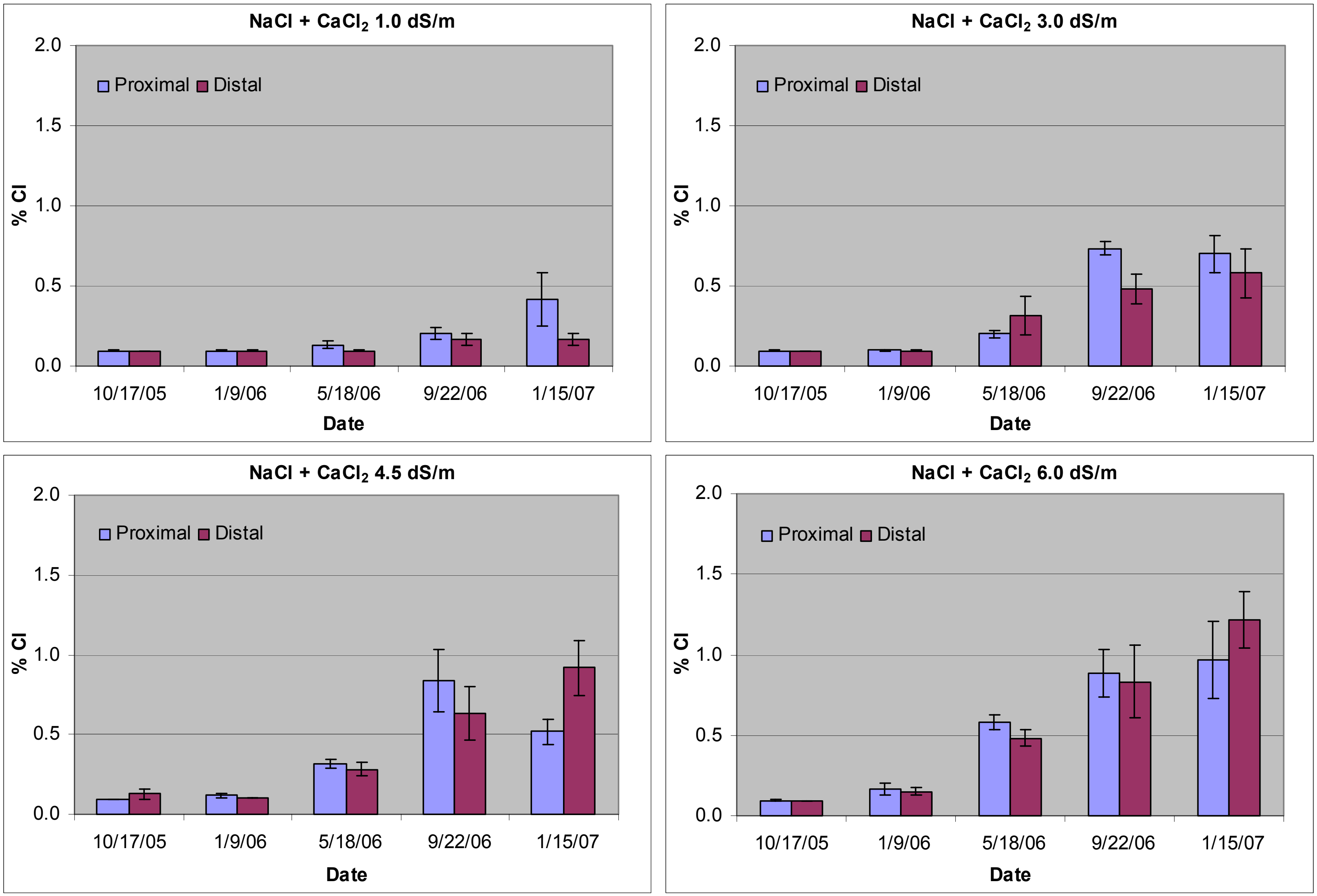

Figure 30. Leaf tissue mean % Cl by section for the NaCl + $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

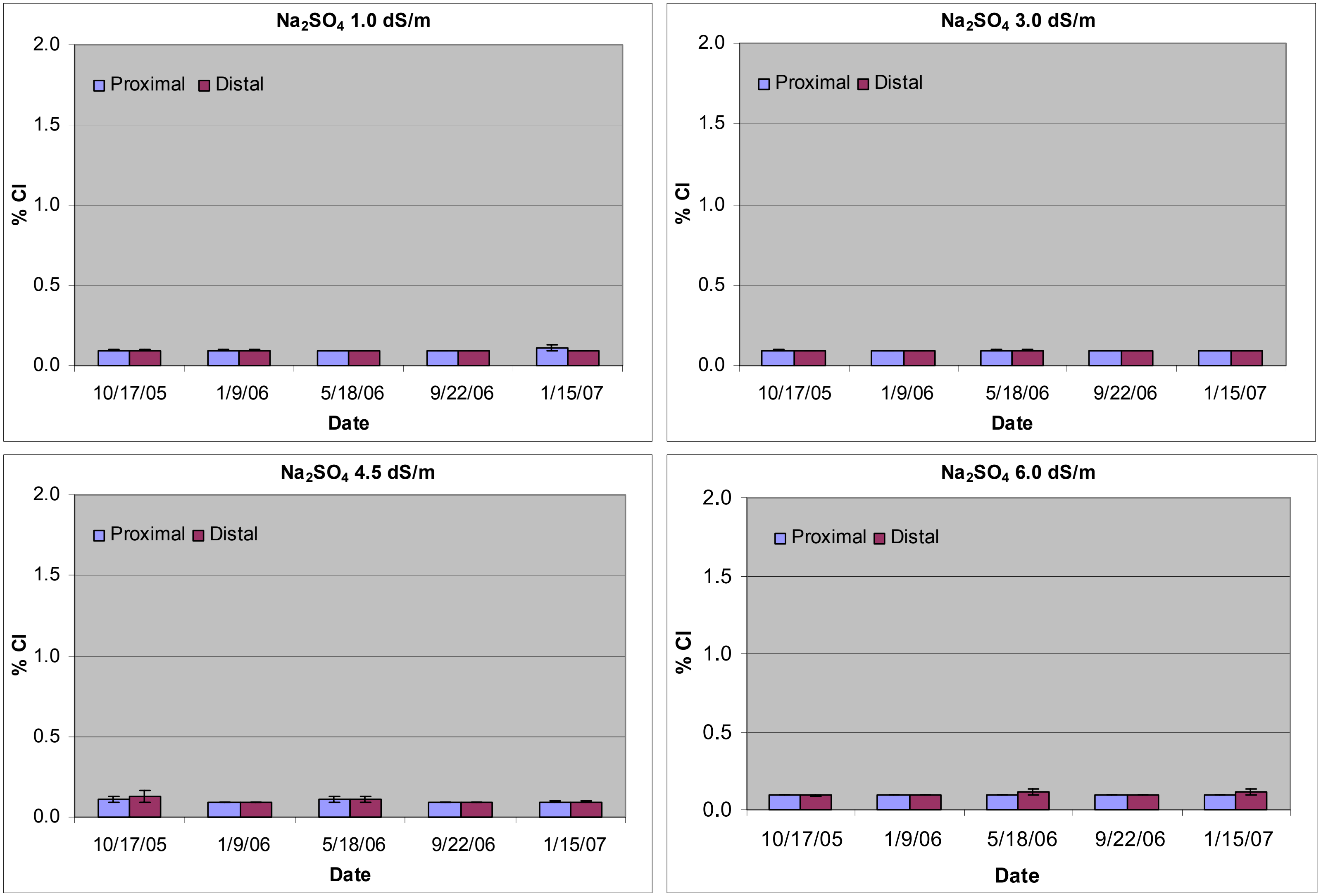

Figure 31. Leaf tissue mean % Cl by section for the Na_2SO_4 treatments across five sampling dates. Error bars indicate ± 1 SE.

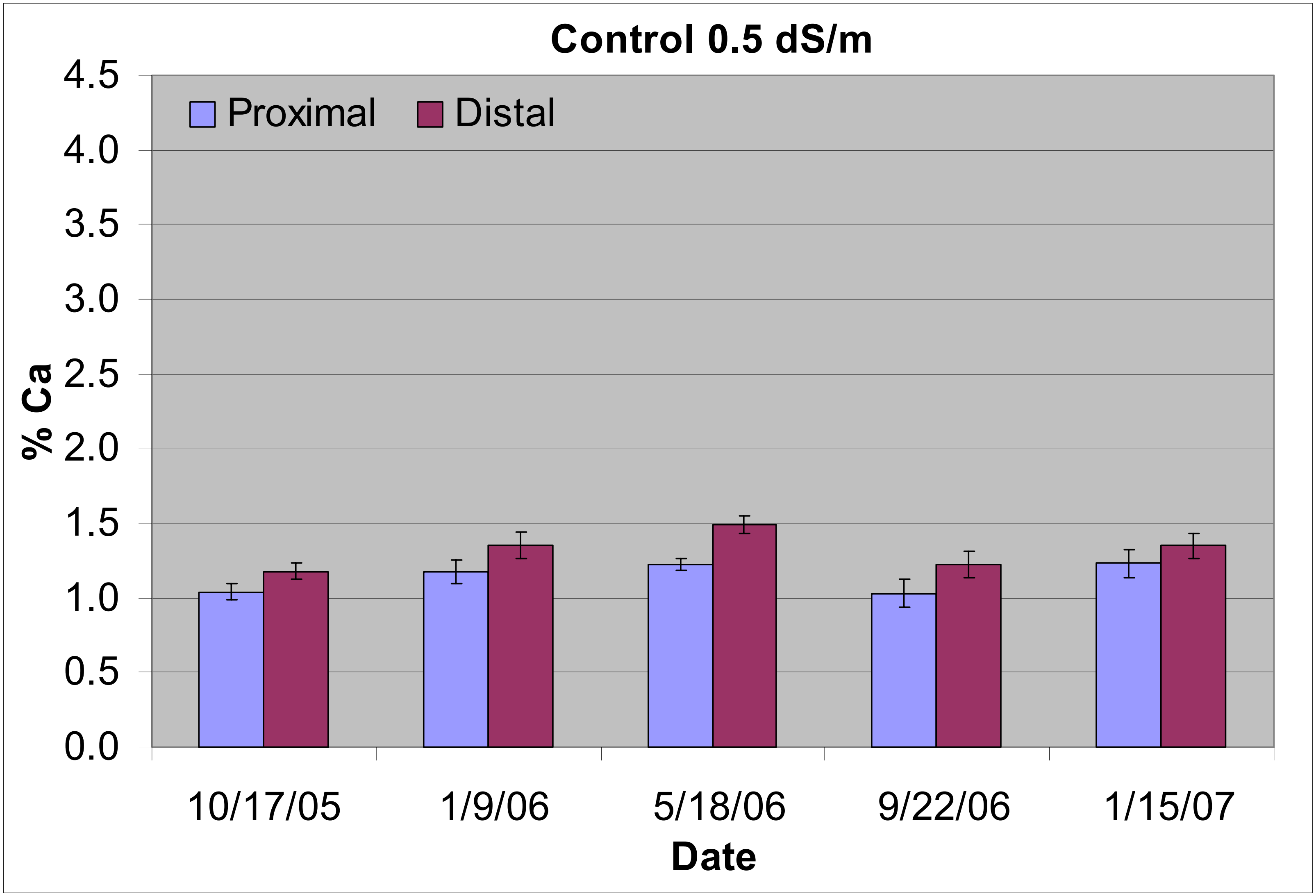

Figure 32. Leaf tissue mean % Ca by section for the control treatment across five sampling dates. Error bars indicate ± 1 SE.

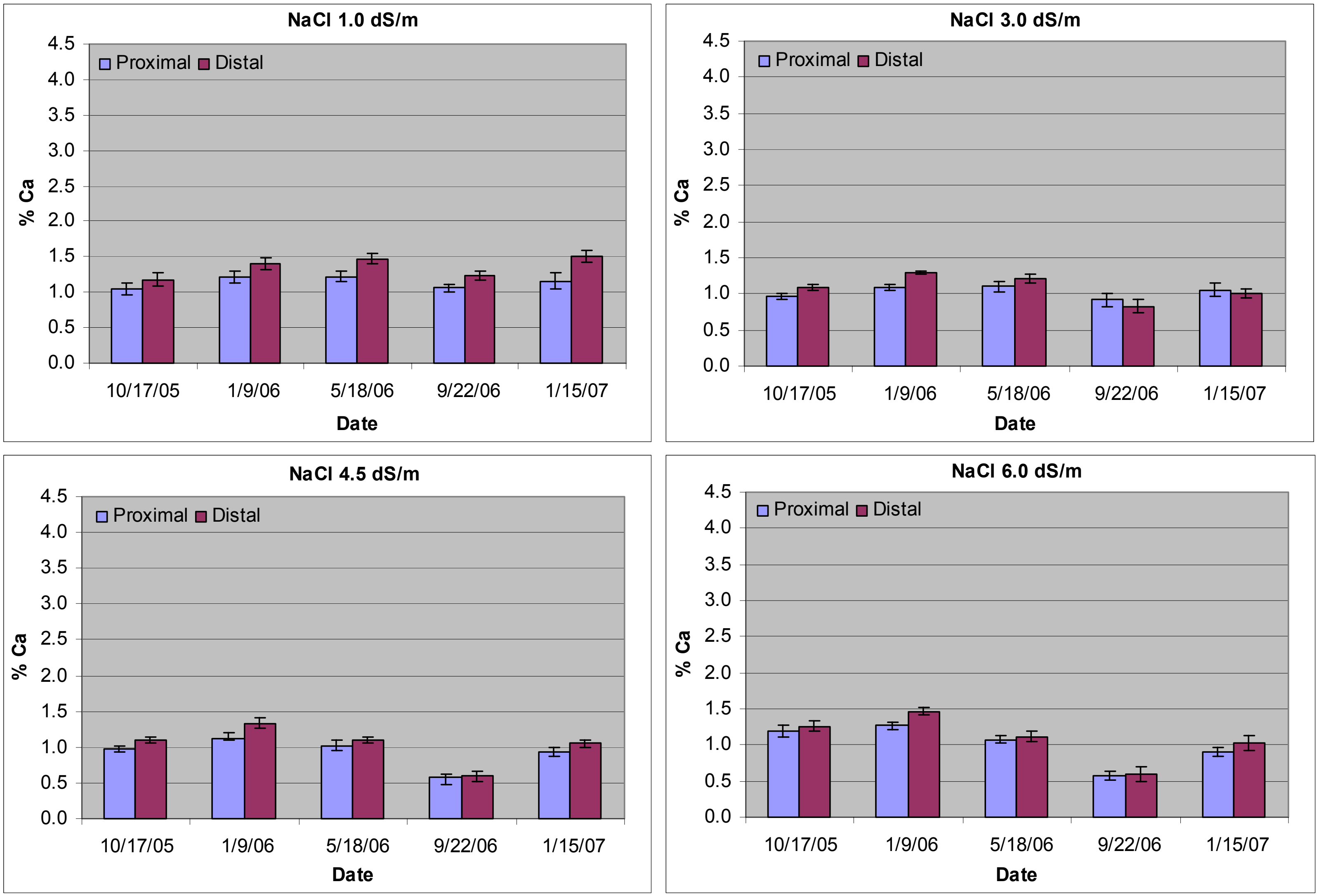

Figure 33. Leaf tissue mean % Ca by section for the NaCl treatments across five sampling dates. Error bars indicate ± 1 SE.

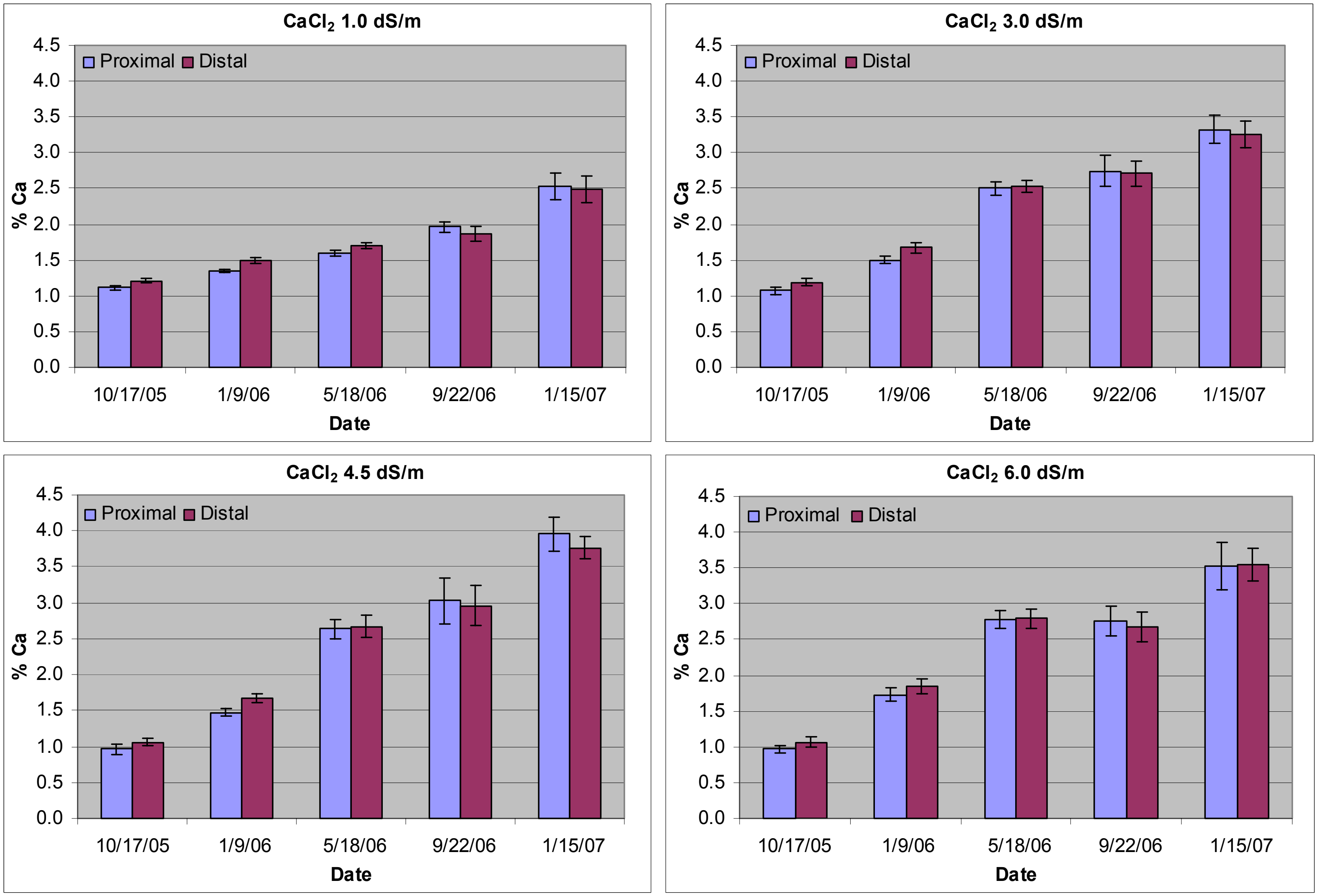

Figure 34. Leaf tissue mean % Ca by section for the $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

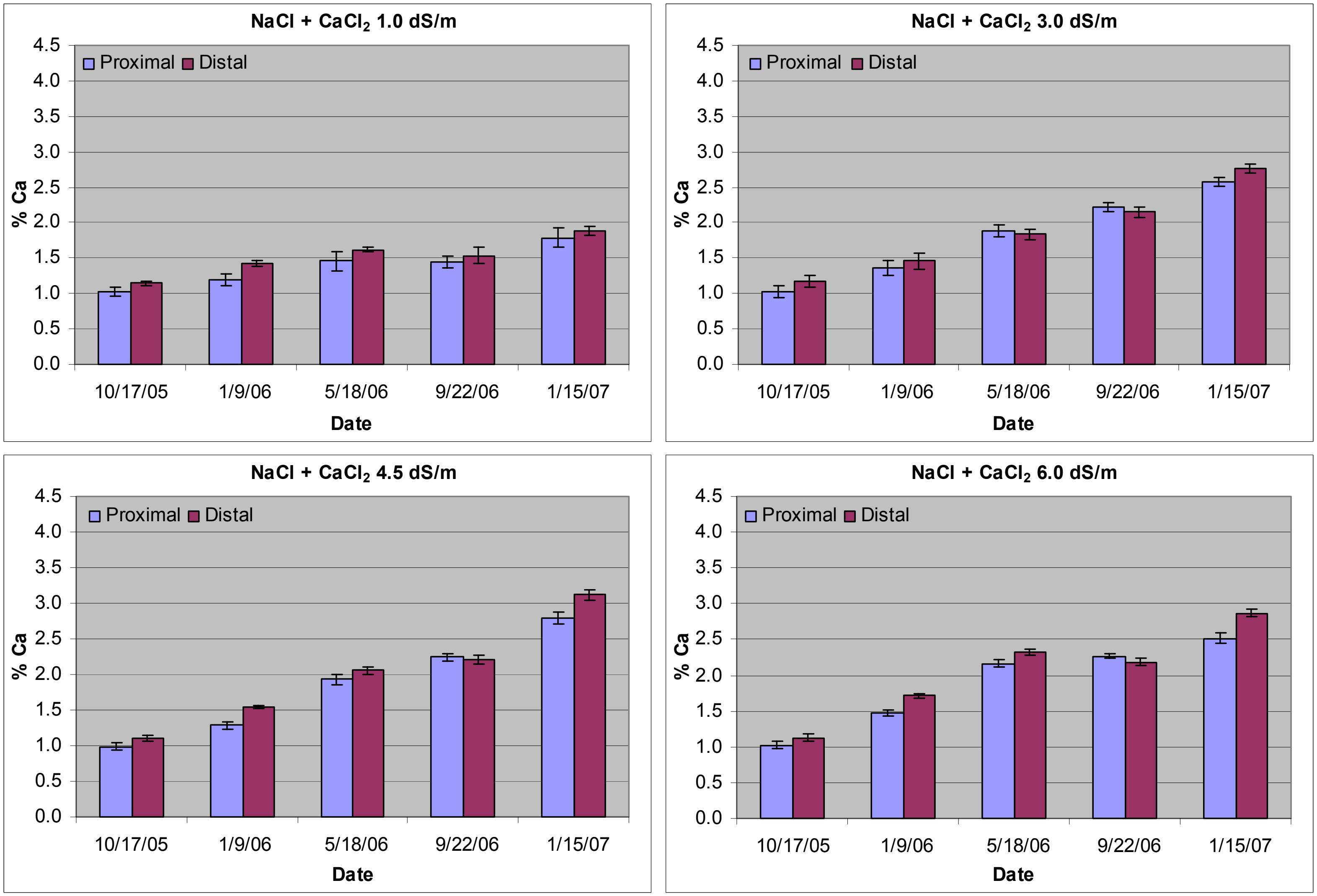

Figure 35. Leaf tissue mean % Ca by section for the NaCl + $CaCl_2$ treatments across five sampling dates. Error bars indicate ± 1 SE.

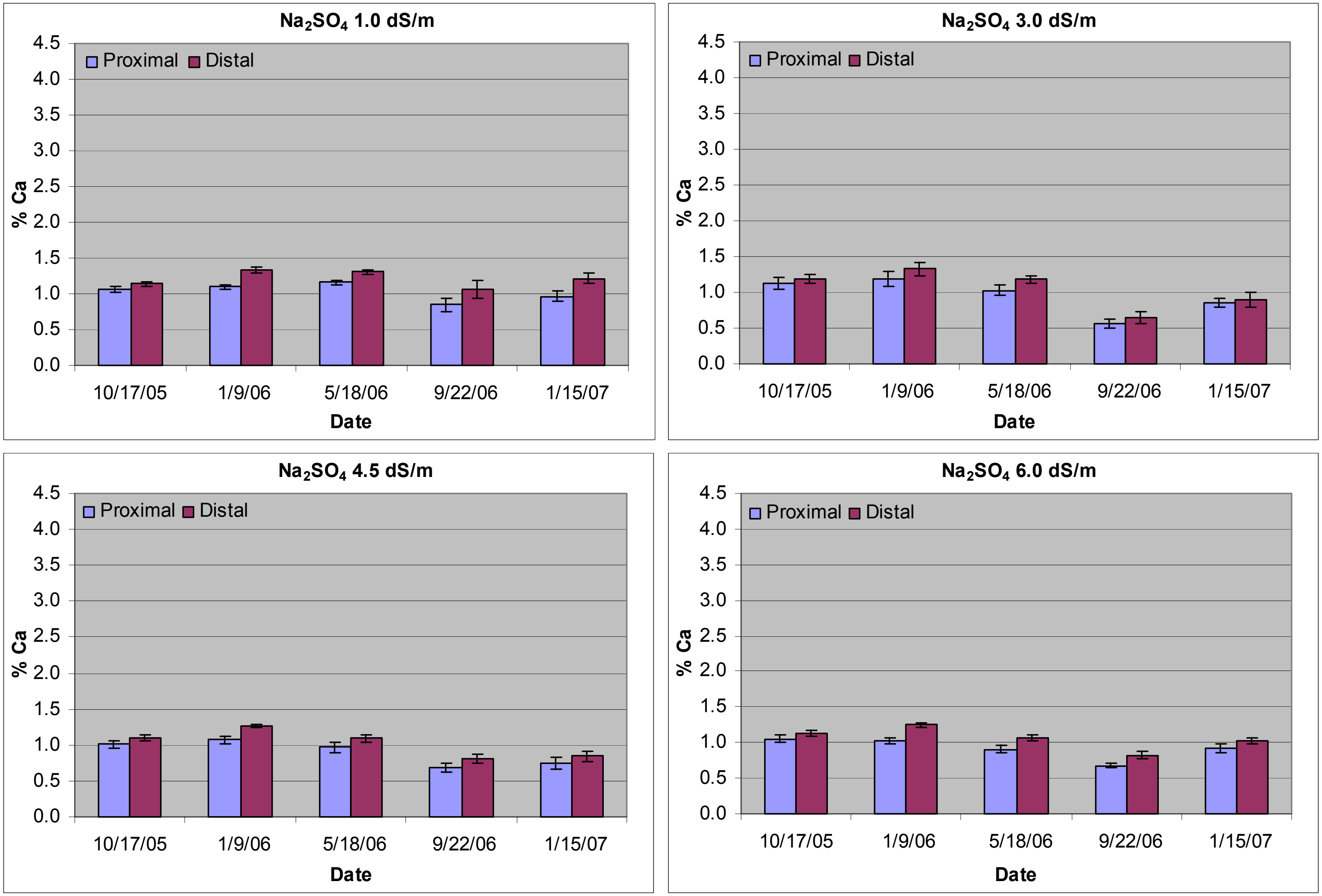

Figure 36. Leaf tissue mean % Ca by section for the Na_2SO_4 treatments across five sampling dates. Error bars indicate ± 1 SE.

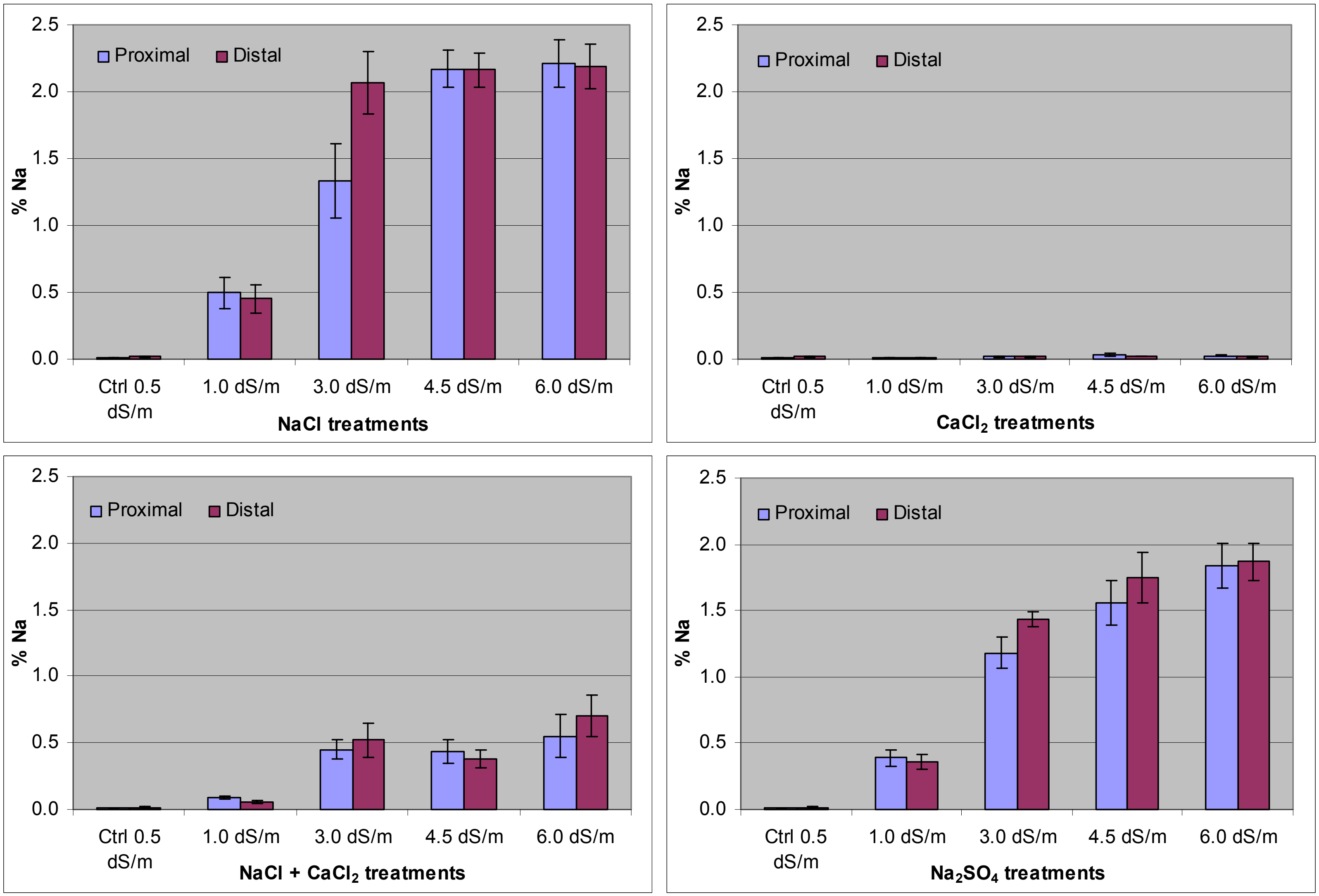

Figure 37. Leaf tissue mean % Na by section for all treatments on 1/15/07. Error bars indicate ± 1 SE.

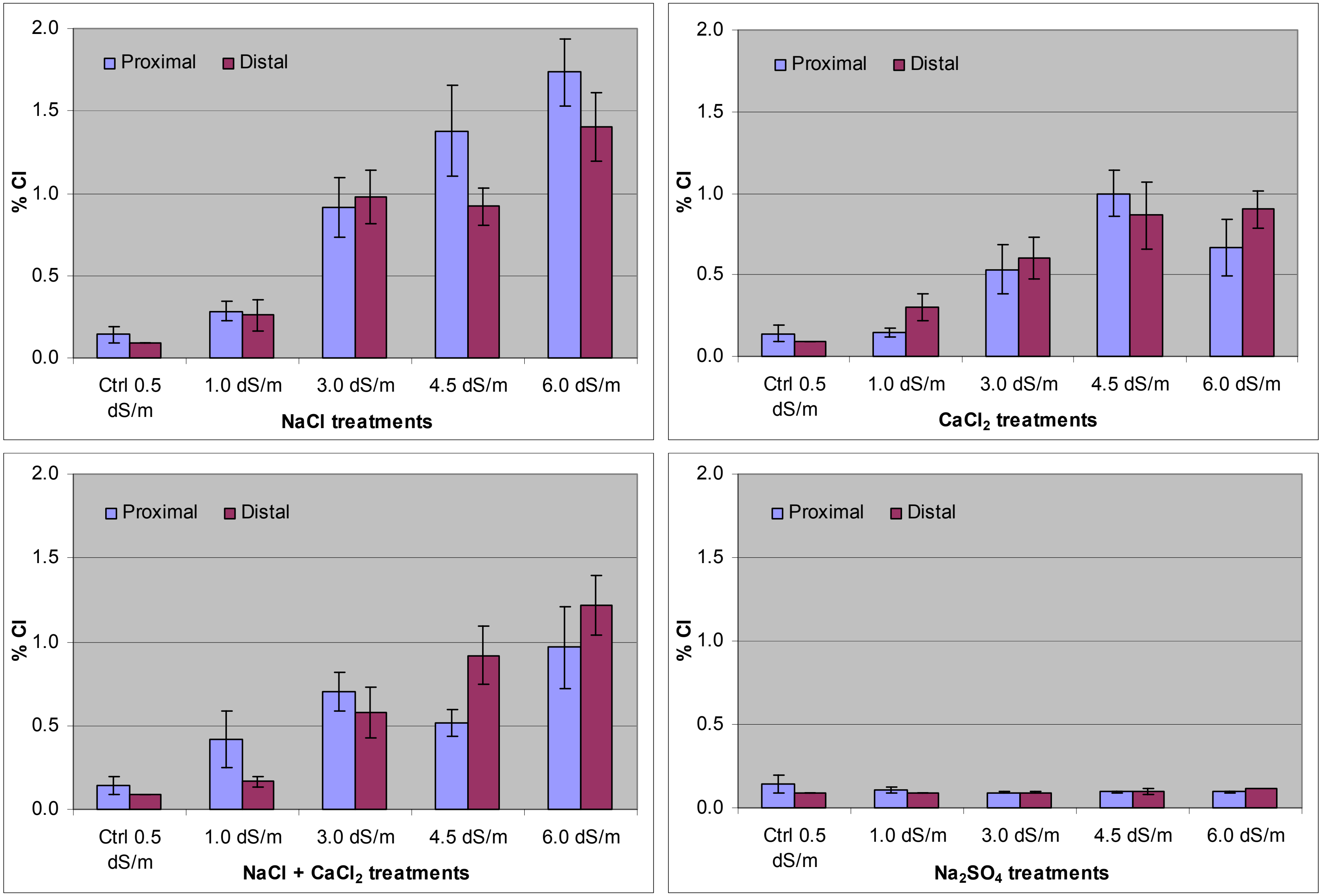

Figure 38. Leaf tissue mean % Cl by section for all treatments on 1/15/07. Error bars indicate ± 1 SE.

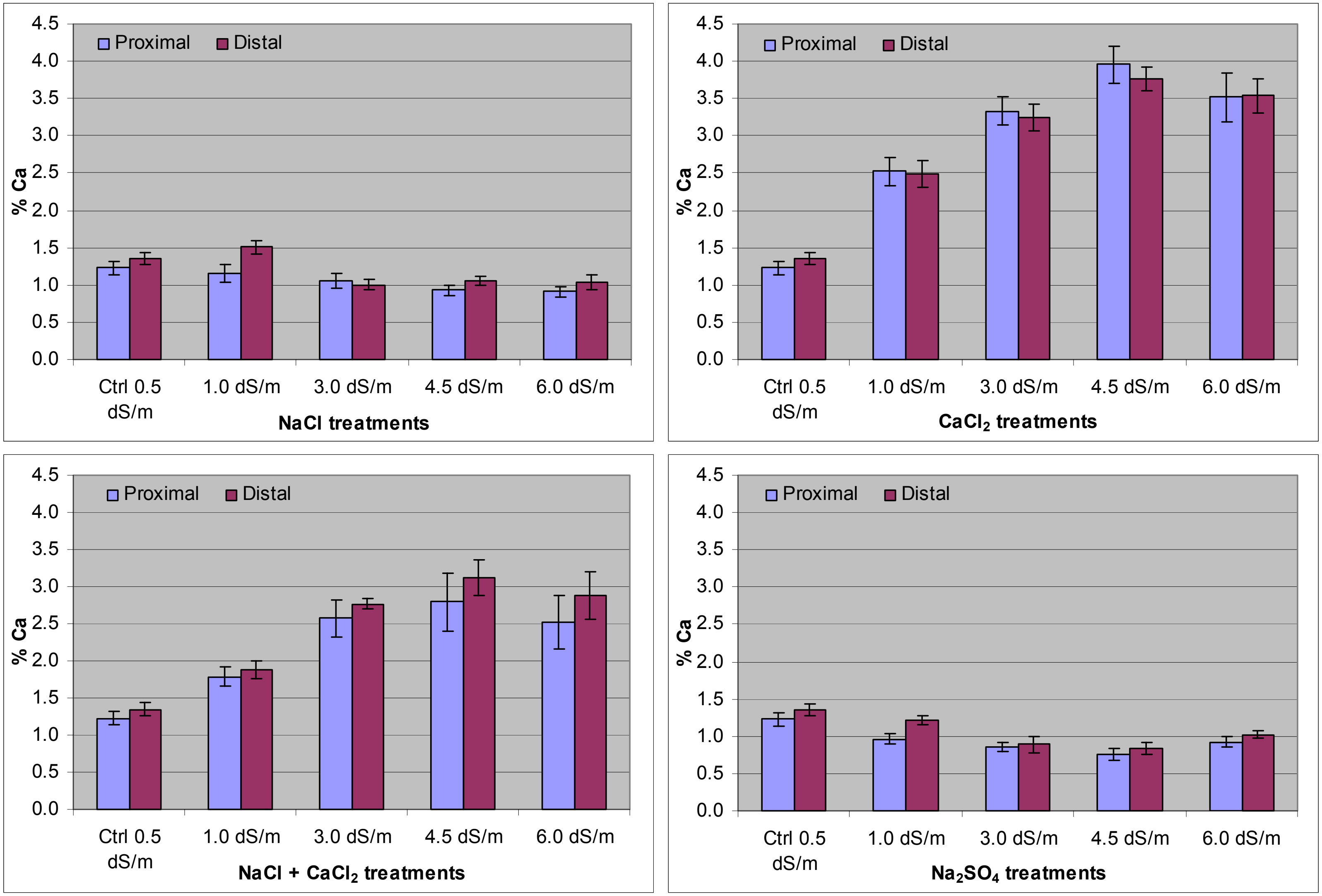

Figure 39. Leaf tissue mean % Ca by section for all treatments on 1/15/07. Error bars indicate ± 1 SE.

Figure 40. Control 0.5 dS/m treatment secondary branches on 1/10/07. All replicates (1-1 to 1-9) are represented and ordered left to right, top to bottom.

Figure 41. NaCl 1.0 dS/m secondary branches on 1/10/07. All replicates (2-1 to 2-6) are represented and ordered left to right, top to bottom.

Figure 42. NaCl 3.0 dS/m secondary branches on 1/10/07. All replicates (3-1 to 3-6) are represented and ordered left to right, top to bottom.

Figure 43. NaCl 4.5 dS/m secondary branches on 1/10/07. All replicates (4-1 to 4-6) are represented and ordered left to right, top to bottom.

Figure 44. NaCl 6.0 dS/m secondary branches on 1/10/07. All replicates (5-1 to 5-6) are represented and ordered left to right, top to bottom.

Figure 45. $CaCl_2$ 1.0 dS/m secondary branches on 1/10/07. All replicates (6-1 to 6-6) are represented and ordered left to right, top to bottom.

Figure 46. $CaCl_2$ 3.0 dS/m secondary branches on 1/10/07. All replicates (7-1 to 7-6) are represented and ordered left to right, top to bottom.

Figure 47. $CaCl_2$ 4.5 dS/m secondary branches on 1/10/07. All replicates (8-1 to 8-6) are represented and ordered left to right, top to bottom.

Figure 48. $CaCl_2$ 6.0 dS/m secondary branches on 1/10/07. All replicates (9-1 to 9-6) are represented and ordered left to right, top to bottom.

Figure 49. NaCl + $CaCl_2$ 1.0 dS/m secondary branches on 1/10/07. All replicates (10-1 to 10-6) are represented and ordered left to right, top to bottom.


Figure 50. NaCl + $CaCl_2$ 3.0 dS/m secondary branches on 1/10/07. All replicates (11-1 to 11-6) are represented and ordered left to right, top to bottom.

Figure 51. NaCl + $CaCl_2$ 4.5 dS/m secondary branches on 1/10/07. All replicates (12-1 to 12-6) are represented and ordered left to right, top to bottom.

Figure 52. NaCl + $CaCl_2$ 6.0 dS/m secondary branches on 1/10/07. All replicates (13-1 to 13-6) are represented and ordered left to right, top to bottom.

Figure 53. Na_2SO_4 1.0 dS/m secondary branches on 1/10/07. All replicates (14-1 to 14-6) are represented and ordered left to right, top to bottom.

Figure 54. Na_2SO_4 3.0 dS/m secondary branches on 1/10/07. All replicates (15-1 to 15-6) are represented and ordered left to right, top to bottom.

Figure 55. Na_2SO_4 4.5 dS/m secondary branches on 1/10/07. All replicates (16-1 to 16-6) are represented and ordered left to right, top to bottom.

Figure 561. Na_2SO_4 6.0 dS/m secondary branches on 1/10/07. All replicates (17-1 to 17-6) are represented and ordered left to right, top to bottom.

Appendix 1. Mean final trunk diameter and tree height.

Treatment	Mean Trunk Diameter (mm) ± 1 SE 1/3/2007	Mean Tree Height (cm) ± 1 SE 1/8/2007
Control 0.5 dS/m	49.97 ± 1.11	254.25 ± 22.91
NaCl 1.0 dS/m	49.94 ± 2.42	230.25 ± 16.52
NaCl 3.0 dS/m	38.88 ± 1.63	173.75 ± 14.24
NaCl 4.5 dS/m	37.49 ± 1.58	187.83 ± 15.66
NaCl 6.0 dS/m	29.82 ± 2.02	158.42 ± 14.73
$CaCl_2$ 1.0 dS/m	46.37 ± 1.43	237.58 ± 25.24
$CaCl_2$ 3.0 dS/m	44.68 ± 1.51	234.58 ± 18.94
$CaCl_2$ 4.5 dS/m	37.68 ± 1.35	209.50 ± 12.72
$CaCl_2$ 6.0 dS/m	32.79 ± 1.18	176.25 ± 9.88
NaCl + $CaCl_2$ 1.0 dS/m	53.39 ± 2.40	231.17 ± 33.74
NaCl + $CaCl_2$ 3.0 dS/m	42.26 ± 2.11	191.25 ± 24.71
NaCl + $CaCl_2$ 4.5 dS/m	39.24 ± 3.42	172.00 ± 13.54
NaCl + $CaCl_2$ 6.0 dS/m	34.34 ± 1.12	190.00 ± 15.77
Na_2SO_4 1.0 dS/m	49.06 ± 1.69	253.08 ± 31.69
Na_2SO_4 3.0 dS/m	40.91 ± 1.75	216.83 ± 16.94
Na_2SO_4 4.5 dS/m	32.37 ± 2.38	174.25 ± 12.59
Na_2SO_4 6.0 dS/m	30.64 ± 0.70	162.67 ± 11.44

Appendix 2. Mean Leaf % Na by date, treatment, and section. Error values indicate ± 1 SE.

Treatment	Section	10/17/05	1/9/06	5/18/06	9/22/06	1/15/07
Ctrl 0.5 dS/m	P	0.17 ± 0.03	0.14 ± 0.02	0.09 ± 0.02	0.13 ± 0.11	0.01 ± 0.00
	D	0.18 ± 0.03	0.15 ± 0.02	0.08 ± 0.02	0.02 ± 0.00	0.02 ± 0.00
NaCl 1.0 dS/m	P	0.15 ± 0.02	0.17 ± 0.02	0.18 ± 0.03	0.37 ± 0.06	0.50 ± 0.12
	D	0.14 ± 0.03	0.15 ± 0.03	0.21 ± 0.04	0.39 ± 0.07	0.45 ± 0.10
NaCl 3.0 dS/m	P	0.16 ± 0.05	0.32 ± 0.03	0.76 ± 0.07	1.22 ± 0.11	1.34 ± 0.28
	D	0.17 ± 0.05	0.38 ± 0.04	0.88 ± 0.16	1.46 ± 0.09	2.07 ± 0.23
NaCl 4.5 dS/m	P	0.15 ± 0.02	0.36 ± 0.04	0.99 ± 0.07	2.07 ± 0.10	2.17 ± 0.14
	D	0.14 ± 0.02	0.43 ± 0.07	1.37 ± 0.12	2.08 ± 0.12	2.17 ± 0.13
NaCl 6.0 dS/m	P	0.15 ± 0.01	0.47 ± 0.03	1.34 ± 0.07	2.74 ± 0.32	2.21 ± 0.18
	D	0.18 ± 0.02	0.68 ± 0.06	2.07 ± 0.15	2.61 ± 0.34	2.19 ± 0.17
$CaCl_2$ 1.0 dS/m	P	0.18 ± 0.04	0.17 ± 0.05	0.07 ± 0.02	0.01 ± 0.00	0.01 ± 0.00
	D	0.19 ± 0.05	0.17 ± 0.05	0.08 ± 0.03	0.01 ± 0.00	0.01 ± 0.00
$CaCl_2$ 3.0 dS/m	P	0.14 ± 0.04	0.13 ± 0.03	0.07 ± 0.03	0.01 ± 0.00	0.02 ± 0.01
	D	0.17 ± 0.05	0.14 ± 0.03	0.08 ± 0.03	0.01 ± 0.00	0.02 ± 0.01
$CaCl_2$ 4.5 dS/m	P	0.15 ± 0.03	0.15 ± 0.03	0.08 ± 0.03	0.02 ± 0.00	0.04 ± 0.01
	D	0.15 ± 0.03	0.15 ± 0.03	0.07 ± 0.03	0.01 ± 0.00	0.02 ± 0.00
$CaCl_2$ 6.0 dS/m	P	0.13 ± 0.02	0.13 ± 0.02	0.05 ± 0.01	0.01 ± 0.00	0.03 ± 0.01
	D	0.12 ± 0.02	0.11 ± 0.02	0.04 ± 0.01	0.01 ± 0.00	0.02 ± 0.00
NaCl + $CaCl_2$ 1.0 dS/m	P	0.16 ± 0.02	0.15 ± 0.03	0.10 ± 0.03	0.12 ± 0.02	0.09 ± 0.01
	D	0.15 ± 0.03	0.14 ± 0.04	0.08 ± 0.02	0.07 ± 0.02	0.06 ± 0.01
NaCl + $CaCl_2$ 3.0 dS/m	P	0.14 ± 0.02	0.17 ± 0.03	0.18 ± 0.02	0.43 ± 0.08	0.45 ± 0.07
	D	0.15 ± 0.03	0.18 ± 0.04	0.18 ± 0.04	0.42 ± 0.10	0.52 ± 0.13
NaCl + $CaCl_2$ 4.5 dS/m	P	0.15 ± 0.02	0.22 ± 0.02	0.24 ± 0.02	0.41 ± 0.06	0.44 ± 0.09
	D	0.15 ± 0.02	0.25 ± 0.03	0.27 ± 0.05	0.35 ± 0.05	0.38 ± 0.07
NaCl + $CaCl_2$ 6.0 dS/m	P	0.15 ± 0.02	0.22 ± 0.03	0.33 ± 0.04	0.53 ± 0.07	0.55 ± 0.16
	D	0.15 ± 0.02	0.27 ± 0.03	0.44 ± 0.05	0.50 ± 0.08	0.70 ± 0.16
Na_2SO_4 1.0 dS/m	P	0.13 ± 0.02	0.15 ± 0.02	0.20 ± 0.03	0.37 ± 0.07	0.39 ± 0.06
	D	0.14 ± 0.03	0.15 ± 0.02	0.24 ± 0.06	0.37 ± 0.06	0.36 ± 0.06
Na_2SO_4 3.0 dS/m	P	0.13 ± 0.02	0.26 ± 0.02	0.58 ± 0.05	1.07 ± 0.12	1.18 ± 0.12
	D	0.13 ± 0.02	0.32 ± 0.04	0.72 ± 0.07	1.30 ± 0.16	1.43 ± 0.06
Na_2SO_4 4.5 dS/m	P	0.12 ± 0.01	0.27 ± 0.04	0.82 ± 0.04	1.18 ± 0.05	1.56 ± 0.17
	D	0.12 ± 0.01	0.29 ± 0.06	1.03 ± 0.07	1.32 ± 0.08	1.75 ± 0.19
Na_2SO_4 6.0 dS/m	P	0.17 ± 0.03	0.39 ± 0.03	1.11 ± 0.06	1.55 ± 0.07	1.84 ± 0.17
	D	0.16 ± 0.03	0.44 ± 0.03	1.34 ± 0.08	1.52 ± 0.07	1.87 ± 0.14

Appendix 3. Mean Leaf % Cl by date, treatment, and section. Error values indicate ± 1 SE.

Treatment	Section	10/17/05	1/9/06	5/18/06	9/22/06	1/15/07
Ctrl 0.5 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.14 ± 0.05
	D	0.09 ± 0.00	0.10 ± 0.00	0.12 ± 0.02	0.11 ± 0.02	0.09 ± 0.00
NaCl 1.0 dS/m	P	0.09 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.30 ± 0.07	0.28 ± 0.06
	D	0.09 ± 0.00	0.10 ± 0.00	0.11 ± 0.02	0.22 ± 0.05	0.26 ± 0.09
NaCl 3.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.25 ± 0.02	0.77 ± 0.04	0.92 ± 0.18
	D	0.10 ± 0.00	0.10 ± 0.00	0.15 ± 0.02	0.80 ± 0.12	0.98 ± 0.16
NaCl 4.5 dS/m	P	0.09 ± 0.00	0.10 ± 0.00	0.43 ± 0.02	0.87 ± 0.11	1.38 ± 0.27
	D	0.09 ± 0.00	0.10 ± 0.00	0.35 ± 0.02	0.45 ± 0.07	0.92 ± 0.12
NaCl 6.0 dS/m	P	0.09 ± 0.00	0.10 ± 0.00	0.98 ± 0.37	1.35 ± 0.16	1.73 ± 0.20
	D	0.09 ± 0.00	0.10 ± 0.00	1.02 ± 0.50	1.28 ± 0.35	1.40 ± 0.21
$CaCl_2$ 1.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.12 ± 0.02	0.17 ± 0.02	0.15 ± 0.02
	D	0.09 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.13 ± 0.02	0.30 ± 0.08
$CaCl_2$ 3.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.20 ± 0.04	0.65 ± 0.13	0.53 ± 0.15
	D	0.09 ± 0.00	0.10 ± 0.00	0.17 ± 0.03	0.43 ± 0.07	0.60 ± 0.13
$CaCl_2$ 4.5 dS/m	P	0.09 ± 0.00	0.10 ± 0.00	0.33 ± 0.07	0.48 ± 0.05	1.00 ± 0.14
	D	0.09 ± 0.00	0.10 ± 0.00	0.28 ± 0.02	0.42 ± 0.07	0.87 ± 0.21
$CaCl_2$ 6.0 dS/m	P	0.10 ± 0.00	0.12 ± 0.02	0.45 ± 0.02	0.67 ± 0.08	0.67 ± 0.17
	D	0.09 ± 0.00	0.12 ± 0.02	0.42 ± 0.03	0.48 ± 0.07	0.90 ± 0.11
NaCl + $CaCl_2$ 1.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.13 ± 0.02	0.20 ± 0.04	0.42 ± 0.17
	D	0.09 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.17 ± 0.03	0.17 ± 0.03
NaCl + $CaCl_2$ 3.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.20 ± 0.03	0.73 ± 0.04	0.70 ± 0.12
	D	0.09 ± 0.00	0.10 ± 0.00	0.32 ± 0.12	0.48 ± 0.09	0.58 ± 0.15
NaCl + $CaCl_2$ 4.5 dS/m	P	0.10 ± 0.00	0.12 ± 0.02	0.32 ± 0.03	0.83 ± 0.20	0.52 ± 0.08
	D	0.13 ± 0.03	0.10 ± 0.00	0.28 ± 0.04	0.63 ± 0.17	0.92 ± 0.17
NaCl + $CaCl_2$ 6.0 dS/m	P	0.10 ± 0.00	0.17 ± 0.03	0.58 ± 0.05	0.88 ± 0.14	0.97 ± 0.24
	D	0.09 ± 0.00	0.15 ± 0.02	0.48 ± 0.05	0.83 ± 0.22	1.22 ± 0.18
Na_2SO_4 1.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.09 ± 0.00	0.11 ± 0.02
	D	0.10 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.09 ± 0.00	0.09 ± 0.00
Na_2SO_4 3.0 dS/m	P	0.10 ± 0.00	0.09 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.09 ± 0.00
	D	0.09 ± 0.00	0.09 ± 0.00	0.10 ± 0.00	0.09 ± 0.00	0.09 ± 0.00
Na_2SO_4 4.5 dS/m	P	0.11 ± 0.02	0.09 ± 0.00	0.11 ± 0.02	0.09 ± 0.00	0.10 ± 0.00
	D	0.13 ± 0.03	0.09 ± 0.00	0.11 ± 0.02	0.09 ± 0.00	0.10 ± 0.00
Na_2SO_4 6.0 dS/m	P	0.10 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.10 ± 0.00	0.10 ± 0.00
	D	0.09 ± 0.00	0.10 ± 0.00	0.11 ± 0.02	0.09 ± 0.00	0.11 ± 0.02

Appendix 4. Mean Leaf % Ca by date, treatment, and section. Error values indicate ± 1 SE.

Treatment	Section	10/17/05	1/9/06	5/18/06	9/22/06	1/15/07
Ctrl 0.5 dS/m	P	1.04 ± 0.05	1.17 ± 0.08	1.22 ± 0.04	1.03 ± 0.09	1.23 ± 0.09
	D	1.18 ± 0.06	1.36 ± 0.09	1.49 ± 0.06	1.22 ± 0.09	1.35 ± 0.08
NaCl 1.0 dS/m	P	1.05 ± 0.08	1.21 ± 0.09	1.22 ± 0.08	1.07 ± 0.05	1.16 ± 0.12
	D	1.18 ± 0.09	1.41 ± 0.08	1.47 ± 0.07	1.23 ± 0.07	1.51 ± 0.08
NaCl 3.0 dS/m	P	0.97 ± 0.04	1.08 ± 0.04	1.10 ± 0.07	0.92 ± 0.10	1.06 ± 0.10
	D	1.09 ± 0.04	1.29 ± 0.02	1.21 ± 0.06	0.83 ± 0.09	1.00 ± 0.07
NaCl 4.5 dS/m	P	0.97 ± 0.04	1.12 ± 0.07	1.01 ± 0.08	0.57 ± 0.05	0.94 ± 0.07
	D	1.10 ± 0.05	1.33 ± 0.07	1.10 ± 0.04	0.59 ± 0.07	1.05 ± 0.06
NaCl 6.0 dS/m	P	1.18 ± 0.08	1.27 ± 0.05	1.08 ± 0.05	0.58 ± 0.06	0.91 ± 0.07
	D	1.26 ± 0.07	1.47 ± 0.05	1.12 ± 0.07	0.60 ± 0.10	1.03 ± 0.10
$CaCl_2$ 1.0 dS/m	P	1.12 ± 0.03	1.35 ± 0.03	1.60 ± 0.04	1.97 ± 0.07	2.53 ± 0.19
	D	1.21 ± 0.04	1.49 ± 0.04	1.70 ± 0.05	1.87 ± 0.11	2.49 ± 0.18
$CaCl_2$ 3.0 dS/m	P	1.07 ± 0.05	1.50 ± 0.05	2.50 ± 0.09	2.74 ± 0.22	3.33 ± 0.19
	D	1.19 ± 0.06	1.68 ± 0.07	2.53 ± 0.08	2.71 ± 0.17	3.26 ± 0.18
$CaCl_2$ 4.5 dS/m	P	0.96 ± 0.07	1.47 ± 0.05	2.64 ± 0.13	3.03 ± 0.32	3.95 ± 0.24
	D	1.06 ± 0.05	1.67 ± 0.06	2.67 ± 0.16	2.96 ± 0.27	3.76 ± 0.16
$CaCl_2$ 6.0 dS/m	P	0.97 ± 0.05	1.73 ± 0.09	2.78 ± 0.13	2.76 ± 0.22	3.52 ± 0.33
	D	1.07 ± 0.06	1.86 ± 0.10	2.79 ± 0.14	2.67 ± 0.21	3.54 ± 0.23
NaCl + $CaCl_2$ 1.0 dS/m	P	1.02 ± 0.07	1.20 ± 0.08	1.46 ± 0.14	1.44 ± 0.09	1.79 ± 0.14
	D	1.15 ± 0.04	1.43 ± 0.07	1.62 ± 0.06	1.54 ± 0.06	1.88 ± 0.11
NaCl + $CaCl_2$ 3.0 dS/m	P	1.03 ± 0.07	1.36 ± 0.07	1.89 ± 0.09	2.22 ± 0.06	2.57 ± 0.24
	D	1.18 ± 0.07	1.46 ± 0.06	1.84 ± 0.10	2.15 ± 0.06	2.77 ± 0.07
NaCl + $CaCl_2$ 4.5 dS/m	P	0.98 ± 0.06	1.29 ± 0.08	1.93 ± 0.07	2.24 ± 0.12	2.79 ± 0.39
	D	1.10 ± 0.06	1.54 ± 0.07	2.06 ± 0.05	2.21 ± 0.08	3.12 ± 0.24
NaCl + $CaCl_2$ 6.0 dS/m	P	1.02 ± 0.08	1.47 ± 0.06	2.16 ± 0.05	2.27 ± 0.23	2.52 ± 0.36
	D	1.13 ± 0.07	1.72 ± 0.06	2.32 ± 0.08	2.18 ± 0.22	2.87 ± 0.32
Na_2SO_4 1.0 dS/m	P	1.06 ± 0.04	1.10 ± 0.04	1.16 ± 0.04	0.85 ± 0.09	0.97 ± 0.08
	D	1.14 ± 0.03	1.33 ± 0.04	1.30 ± 0.04	1.06 ± 0.12	1.22 ± 0.07
Na_2SO_4 3.0 dS/m	P	1.13 ± 0.08	1.19 ± 0.11	1.03 ± 0.08	0.56 ± 0.07	0.86 ± 0.06
	D	1.19 ± 0.06	1.32 ± 0.09	1.18 ± 0.05	0.64 ± 0.08	0.89 ± 0.10
Na_2SO_4 4.5 dS/m	P	1.01 ± 0.05	1.08 ± 0.05	0.97 ± 0.07	0.69 ± 0.05	0.75 ± 0.08
	D	1.09 ± 0.05	1.26 ± 0.02	1.09 ± 0.05	0.81 ± 0.07	0.84 ± 0.08
Na_2SO_4 6.0 dS/m	P	1.06 ± 0.05	1.03 ± 0.04	0.91 ± 0.05	0.68 ± 0.03	0.92 ± 0.07
	D	1.13 ± 0.05	1.25 ± 0.03	1.08 ± 0.04	0.82 ± 0.05	1.02 ± 0.05

Evaluation of Local Soils for Susceptibility to Structural Degradation From Irrigation

Final Report to the Santa Clara Valley Water District

Jocelyn Marie Beaudette
August 28, 2007

Revised by M.J. Singer
November 2007

Executive Summary

Significant quantities of treated wastewater are used for irrigation in California. The major advantage of using treated wastewater for irrigation is reducing use of potable water that is in short supply. Using treated wastewater comes with some risks, one of which is that the chemistry of the treated wastewater can reduce the rate that irrigation or rainwater enters the soil. Surface soil structure controls the rate water enters soil. Structure may be destroyed, forming a very slowly permeable seal or crust if sodium from the irrigation water increases the soil sodium concentration and high quality (low electrical conductivity) water is used as irrigation water. Natural precipitation, which has low electrical conductivity, will have the same effect as low electrical conductivity irrigation water.

This study used laboratory columns packed with thirty different Santa Clara County soils to determine the effect of different sodium concentrations (measured as sodium adsorption ratio) and different water quality (measured as electrical conductivity) on the rate of water movement through the soils. Saturated hydraulic conductivity and flow rates were used as measures of treatment affect. Small columns without grass and a few large columns on which grass was grown were the experimental units. Low EC water reduced the saturated hydraulic conductivity for all soils. Soils were subdivided into four groups based on changes in Ksat as EC declined. A threshold reduction of 15% from the concentrated solution concentration treatment was used as the basis for the grouping. The Villages 6, Shoreline 8b and 4a soils were the least affected. The Zamora, Wilson School NE side, Villages 7 and 1 and Shoreline 7a, 10a, 7b, and 8a reached the threshold at 5 mmolc/L solution concentration. The Wilson School pit 1, Villages 4, Shoreline 4b and 10b and Garretson series reached the threshold at 10 mmolc/L. The Yolo series, Wilson School near Benton sample, Villages 10, Shoreline 2a and 2b, Pleasanton and Hillgate soil series reached the threshold at 50 mmolc/L and the remaining soil series reached the threshold at 100 mmolc/L.

The effect of SAR at 12 and below was variable. Soils with higher clay contents were more affected by changes in SAR and EC than those with lower clay contents. Two Shoreline samples in columns with grass cover, run at SAR 3 and 12, had ambiguous results. Three of the four columns showed the expected behavior of decreasing saturated hydraulic conductivity with lower salt concentration in the leaching solution. The SAR 3 solution had no effect on the saturated hydraulic conductivity of the Shoreline 4a sample.

Acknowledgements

This project was funded, in large part, by a contract with the Santa Clara Valley Water District. The University of California Agricultural Experiment Station provided additional financial support. We appreciate and acknowledge the support provided by the District and in particular appreciate the support of Robert Siegfried, our main contact with the District. We thank managers of the Shoreline Golf Course and Villages Golf and Country Club, individual land owners and operators in Santa Clara County and the administration of the Wilson Adult School for giving us access to their property. We thank Jim Oster, retired Specialist with the UC Cooperative Extension Service who helped guide the research and helped to manage the project. We thankfully acknowledge the helpful comments made on an earlier draft by three reviewers.

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Chapter 1

1.0 Introduction

1.1 Wastewater as a Resource for Turf Irrigation

1.1.1 Importance of Recycled Wastewater

It is estimated that Californians use 51,200 million gallons of water every day and that California's population will reach 46 million by the year 2020, a 54 percent increase from 29.8 million in 1990 (Hutson et al., 2004). While demand for water increases, surface and groundwater sources will only remain static or decline. In an effort to conserve potable water, the use of recycled wastewater in certain sectors is rising. The California Department of Water Resources estimated that the use of recycled water for landscape irrigation increased from 40,000 acre-feet per year in 1987 to more than 111,000 acre-feet in 2002 (Jones, 2000). This shift in water use is primarily in response to the growing demand for potable water by the municipal sector as California's population increases.

Because of our semi-arid climate and limited annual water supply, land managers face the possibility that at any time, delivery of water supplies may be diverted, delayed or stopped. A recent case in point was the Fall 2007 temporary shut down of the pumps that deliver water to the California aqueduct due to concerns about the endangered Delta Smelt. Thus, many managers are altering their irrigation practices to include the partial or total use of recycled water.

> "In addition to providing a dependable, locally-controlled water supply, water recycling provides tremendous environmental benefits. By providing an additional source of water, water recycling can help us find ways to decrease the diversion of water from sensitive ecosystems." (Yoshikawa et al., 2007).

By 2002, the State Water Resources Control Board estimated that of the total, annual, recycled water used in California (approximately 525,000 acre-feet), about 21 percent went toward landscape irrigation (Karajeh et al., 2004). Additional benefits from the use of recycled wastewater include reduced costs of wastewater treatment and disposal, and potential cost savings to land managers if the cost rate of the recycled water is less than that of the local potable water.

The Santa Clara Valley Water District is one of the California entities that aims to maximize water use efficiency. A district that serves 1.7 million residents and more than 200,000 commuters, Santa Clara has developed a Water Use Efficiency Unit to manage programs in water conservation, water recycling and desalination.

> "While the primary goal of water use efficiency programs is to use water more efficiently, other benefits include energy savings and less emission of greenhouse gases and reactive organic gases. The district estimated energy savings from the district's water conservation and water recycling programs to be more than 196 million kWh for fiscal year 2004-05 and more than 1.3 billion kWh since the programs began in 1992." (Larabee and Ashktorab, 2006).

1.1.2 Recycled Wastewater Production

Grey-water is non-industrial wastewater generated from domestic uses such as washing dishes, laundry and bathing. It comprises 50-80 percent of residential wastewater (Al-Jayyousi, 2003). When grey-water is used for landscape irrigation, tertiary or advanced treatment is required to modify the water to an acceptable quality as determined by the US Environmental Protection Agency. In order to achieve this quality, the water first undergoes primary treatment, where sedimentation is used to separate solids (including greases) from liquids.

”Suspended solids can lead to the development of sludge deposits and anaerobic conditions when untreated wastewater is discharged in the aquatic environment. Excessive amounts of suspended solids cause plugging in irrigation systems.” (Harivandi, 1994).

Additional primary treatment methods include the use of screens, filters, and grit chambers. A secondary biological treatment is then applied to reduce dissolved organic matter from the wastewater.

“Biodegradable organics are comprised principally of proteins, carbohydrates and fats. If discharged to the environment, their biological decomposition can lead to the depletion of dissolved oxygen in receiving waters and to the development of septic conditions.” (Harivandi, 1994).

Secondary treatments include fixed film systems, suspended film systems and lagoon systems that take advantage of microorganisms to convert complex organic matter into less complex organic material that is then metabolized by organisms. The tertiary (or final) treatment focuses on the removal of pathogens, nutrients, and heavy metals. While the pathogens and heavy metals are removed for health and safety reasons, nutrients are removed because of their potential for eutrophication when discharged back into the environment.

1.1.3 Wastewater Byproducts and Implications For Irrigation

Recycled water, though subjected to the rigorous treatments described above, still contains many dissolved solids that may be unwelcome by turf grass managers. Total salt content may be concentrated enough to affect turf growth while specific ion concentrations may affect infiltration rates and permeability. In particular, wastewater tends to have elevated levels of sodium (Na) that have negative affects on the hydraulic behavior of many soils. These affects are magnified under conditions of low electrolyte concentrations. There are a few parameters that describe these conditions and are useful in discussing soil condition and management.

A *saline* soil is characterized by an accumulation of soluble salts that negatively affect the normal growth and development of plants. It is commonly accepted that a soil is saline if the EC (electrical conductivity) of its saturated paste extract is above 4 dS/m (United States Salinity Laboratory Staff, 1954). Electrical conductivity is a measurement of the ability of a solution to conduct electricity and is directly related to the concentration of dissolved salts.

A *sodic* soil contains Na levels high enough to adversely impact soil structure and crop production. The sodicity of a soil can be determined by measuring its exchangeable sodium percentage (ESP), or its sodium adsorption ratio (SAR). ESP is an index of soil sodium content found by comparing the amount of sodium on a soils exchange complex to its cation exchange capacity (which for most soils, can be calculated by computing the sum of the concentrations of the major cations: sodium, magnesium, calcium and potassium). Equation 1.1 is used to calculate exchangeable sodium percentage where the prefix 'X' indicates that the cation is located on the exchange complex (i.e. XNa is exchangeable sodium).

$$ESP = \frac{XNa}{XNa + XCa + XK + XMg} * 100 \qquad (1.1)$$

SAR is a water quality measurement. It is a modified ratio of sodium to calcium and magnesium, measured in a soil solution. It can indicate soil sodicity because in most cases, the cations (and their relative concentrations) on a soil's cation exchange complex, mirror those found in the surrounding solution. The two mediums generally reflect each other because of the contact and tendency towards chemical equilibrium. Equation 1.2 is used to calculate sodium adsorption ratio. The symbols are the same as those used in equation 1.1.

$$SAR = \frac{XNa}{\sqrt[2]{\frac{XCa + XMg}{2}}} \qquad (1.2)$$

Sodium can alter the physical and chemical properties of soil causing long-term damage to its structure and management (Shainberg and Singer, 1990). Larger Na fractions in the soil solution and on the soil's exchange complex lead to increased soil swelling and dispersion. These are two separate processes, but elevated levels of swelling can lead to dispersion.

Swelling can be caused both by high levels of sodium, and by low total salt concentrations. In the case of a sodic soil, the large monovalent sodium ion on the exchange complex causes clay platelets to move apart. When a soil solution's electrolyte concentration is low, swelling occurs as a result of the incorporation of water into the interlayer of clay minerals as osmosis pulls ions from the interlayer into the ambient soil solution. As the interlayer cation concentration decreases, repulsive forces between the diffuse double layers increase and enhance the swelling of soils. If the conditions which caused the soils to swell are modified, (either the sodium levels are lowered or total electrolyte levels raised), it is possible that soils may go through the reverse process, dewatering or shrinking. Because the original particle associations and orientations are retained, soil shrink-swell is a reversible process. In contrast, dispersion is an irreversible process where re-flocculation of soil particles does not result in the original particle associations and orientations. Dispersion is the condition of separated soil particles and is also affected by sodium and electrolyte concentration. (Shainberg and Singer, 1990; Essington, 2004).

1.2 Early Research

1.2.1 Work by Quirk and Schofield

Quirk and Schofield were some of the first researchers to examine the permeability of a soil as a function of ESP and total salt concentration. They tested both the permeability of single ion systems and the permeability of mixed ion systems. In the single ion system, soil pads were initially saturated with concentrated solutions of NaCl, KCl, $MgCl_2$ or $CaCl_2$. The permeability of these pads was then recorded as increasingly dilute solutions of these single ions were passed through the soil pads. They analyzed the results and compared the systems using the ”threshold” concentration given by each cation. The threshold concentration was defined as such because of the physical

> “The concentration of salt which causes a 10 to 15 percent decrease in soil permeability is defined as the threshold concentration.” (Quirk and Schofield, 1955).

and chemical responses (swelling and dispersion) that begin to occur in the soil at that solution concentration. It is not an absolute measure but can be used as a convenient reference level. This study found that the threshold concentration was greatest using NaCl, followed by KCl, $MgCl_2$ and was the least for $CaCl_2$. These values are listed in Table 1.1.

Table 1.1. Threshold concentrations and pH for Sawyers I (Quirk and Schofield, 1955).

Salt	Threshold concentration (molar)	pH
NaCl	2.5×10^{-1}	5.2
KCl	6.7×10^{-2}	5.4
$MgCl_2$	1.0×10^{-3}	5.4
$CaCl_2$	3.0×10^{-4}	5.4

Practically, this means that soil structure is best maintained under low electrolyte conditions in the presence of $CaCl_2$, and is least well maintained under low electrolyte conditions in the presence of NaCl.

> “In fact, for the calcium-saturated soil the permeability to distilled water is not very different from the permeability to 3 x 10^4 M calcium chloride; whereas the sodium-saturated material became almost impermeable when 1 x 10^2 M sodium chloride was used.” (Quirk and Schofield, 1955).

To test the permeability of mixed ion systems, four samples of a soil were brought to equilibrium with solutions of varying Na/Ca ratios followed by applications of increasingly dilute solutions until the threshold concentration was determined (the original Na/Ca ratio was maintained throughout the dilution sequence). The initial solution concentrations and approximate threshold concentrations for this series are listed in Table 1.2. It was found that the soil with the highest percentage of exchangeable Na had the highest threshold concentration. Likewise, the soil with the lowest percentage of exchangeable Na had the lowest threshold concentration. Thus, soils with higher relative Na percentages are least able to maintain soil structure under low electrolyte conditions.

Table 1.2. Exchangeable sodium percentages and threshold concentrations for Na-Ca mixtures (Quirk and Schofield, 1955).

Series	NaCl (M)	$CaCl_2$ (M)	Exchangeable Na (%)
1	0.01	0.01	5.0
	0.00225	0.0004	5.8
2	0.02	0.01	8.1
	0.0048	0.0004	8.9
3	0.05	0.01	16.1
	0.01125	0.0004	21.0
4	0.1	0.01	32.2
	0.0227	0.0004	35.2

1.2.2 Work by McNeal and Coleman

McNeal and Coleman (1966) expanded on the work of Quirk and Schofield (1955) by testing the hydraulic conductivities of seven soils with solutions of varying SAR and EC. Each soil was packed in a Plexiglas permeameter, treated with CO_2 and saturated with a 0.8 N salt solution of the appropriate SAR. Sodium adsorption ratios used included ∞ (pure NaCl), 100, 50, 25, 20, 15, 10, 5 and 0 (pure $CaCl_2$). After saturation, a sequence of solutions (5 pore volumes each) was passed through the soil, and hydraulic conductivity measurements were obtained for each. For a given sequence, the SAR was held constant while total salt concentrations became increasingly dilute. Total salt concentrations of the dilution sequence included 800 (initial saturation solution), 200, 50, 12.5, and 3.13 meq/L. Results from their study revealed that:

> "For five of the seven soils...the hydraulic conductivity to $CaCl_2$ solutions (SAR = 0) was invariant with increasing time and with decreasing salt concentration. This indicates both a high degree of structural stability for the Ca-saturated systems, and the repression of significant microbial activity through the action of the added $HgCl_2$. At the other extreme, using NaCl solutions (SAR= ∞), the hydraulic conductivity for all but the Aiken and Vale soils decreased drastically as the salt concentration was decreased from 800 to 3.13 meq/liter."

The hydraulic behavior of two of the seven soils is shown in Figure 1.1.

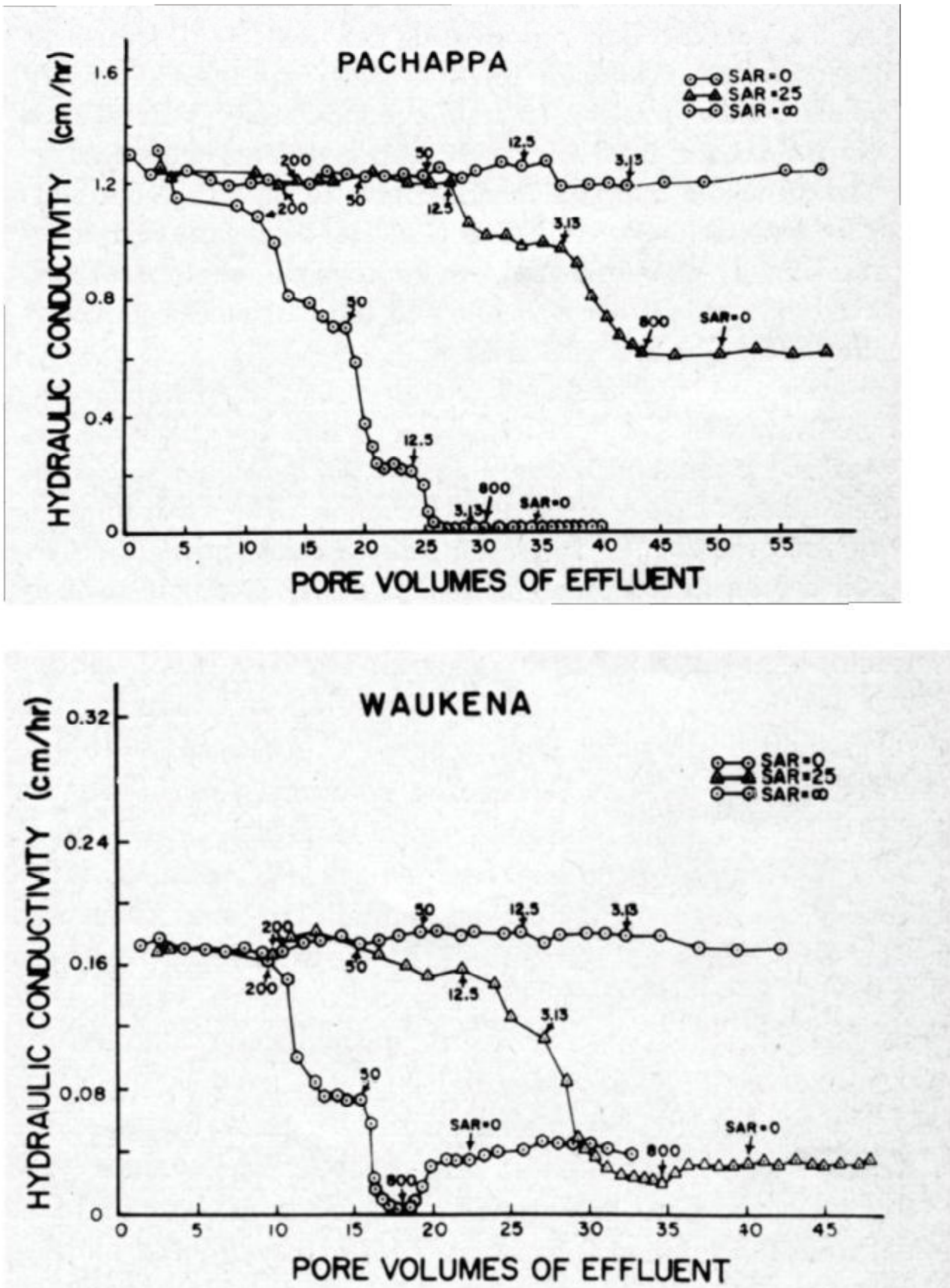

Figure 1.1: Hydraulic conductivity of the (a) Pachappa and (b) Waukena soils at SAR 0, 25 and infinity (McNeal and Coleman, 1966).

1.2.3 Work by Suarez, Wood and Lesch

Suarez et al. (2006) recently published work that focused on the effects of SAR and EC under simulated rainfall. A clay and a loam soil were studied under alternating periods of simulated rainfall, irrigation and drying. The soils were packed into plastic containers that held ceramic extractors overlain by 7 cm of fine sand and topped with 17 cm of lightly packed soil. The water qualities of the irrigation solution included unique combinations of SAR 2, 4, 6, 8, and 10 and EC 1.0 and 2.0 dS/m. The averaged results for the two soils from the last rain event are shown in Figure 1.2.

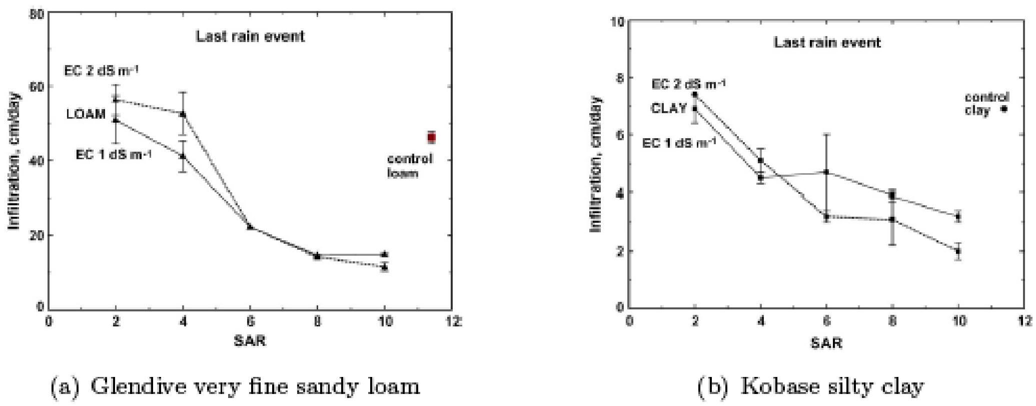

Figure 1.2: Relationship among infiltration rate, SAR and EC for the loam and clay soils during the last rain event. (Suarez et al., 2006).

Although this was not a column study, the conclusions from this experiment were parallel to the work of Quirk and Schofield and McNeal and Coleman. As the SAR of the irrigation water increased, soil infiltration rates for both the loam and the clay soil types decreased.

> "The relative increase in infiltration times with increasing SAR was comparable for both soil types." (Suarez et al., 2006).

1.3 Project intent

As put forth by Research agreement No. 2977 between the Santa Clara Valley Water District and the Regents of the University of California, the objective of this project was to ascertain the treatment levels of recycled waters required for sustainable use of these waters for landscape and crop irrigation. In particular, this project was designed to determine the hydraulic behavior of a subset of soils from Santa Clara County when various water qualities were applied. These data will be available to land managers to determine best management practices for irrigating with recycled water. The recycled water is/will be provided by the Palo Alto Regional Water Quality Control Plant (RWQCP) and used for landscape irrigation within the Mountain View/Moffett area. A 2003 RWQCP water analysis found a normal range of constituents including an average SAR of 5 and an average EC of

1.54 dS/m.

Chapter 2

2.0 Materials and Methods

2.1 Sample Collection

2.1.1 Project sites

Thirty soil samples were collected for analysis from Santa Clara County (Figure 1.3). These sites were chosen to maximize variation in soil physical and chemical characteristics to determine a maximum possible range of soil hydraulic behaviors when treated with various water qualities. Sampled sites included two golf courses (Shoreline Golf Links and Villages Golf and Country Club), an adult school, and several county parks.

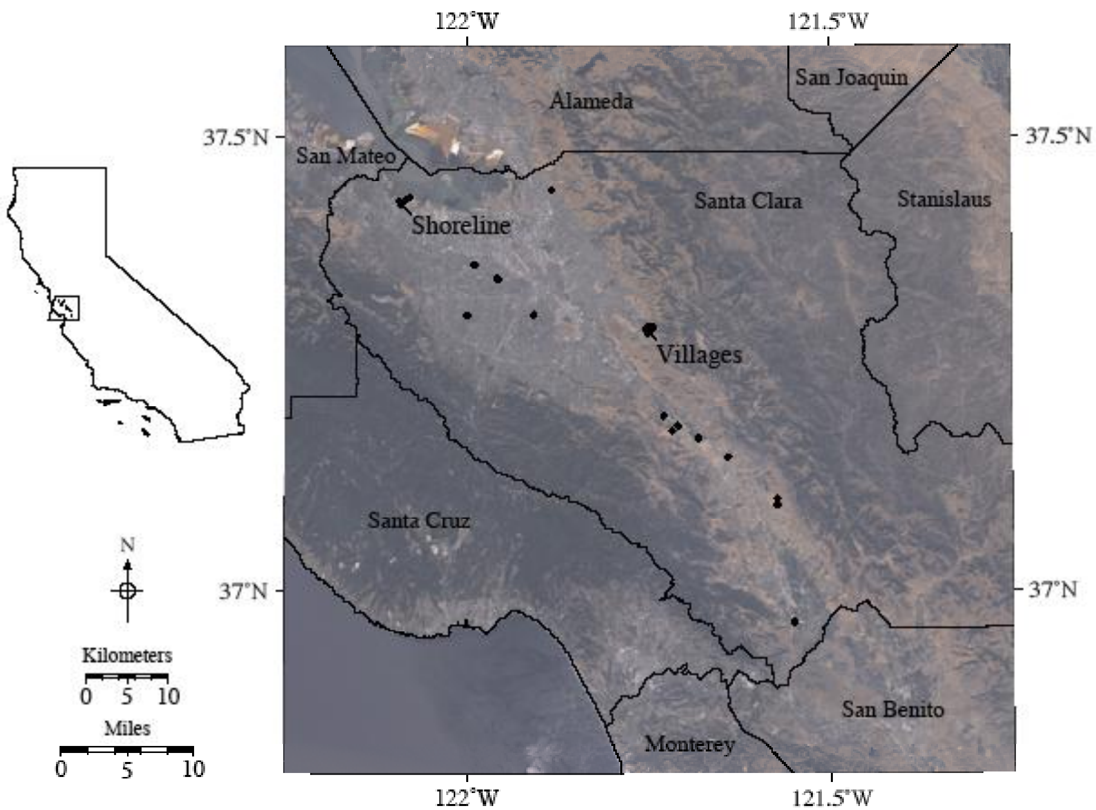

Figure 1.3: Sample sites in Santa Clara County. Note that the two golf courses (Shoreline and Villages) have been labeled but for simplicity, the county parks have not been labeled.

GPS locations of all sites were recorded to sub-meter accuracy using the NAD83 datum (Table 1.3). Note that the Shoreline samples are modified with either an "a" (indicating a 0-6 inch sample depth) or a "b" (indicating a 6-12 inch sample depth). The numbers for the Shoreline and

Villages golf courses correspond to those on Figures 1.4 and 1.6 respectively.

Table 1.3: Geographic coordinates of all sample locations and their respective labels.

Sample ID	Longitude W	Latitude N
Arbuckle series	121°38’26.00”	37°08’50.53”
Campbell series	121°43’44.13”	37°11’33.64”
Cardoza series	121°52’58.509”	37°26’28.986”
Clear Lake series	121°43’04.02”	37°10’34.93”
Garretson series	121°54’29.398”	37°18’15.942”
Hillgate series	121°34’23.851”	37°5’41.963”
Machado series	121°59’22.536”	37°21’32.777”
Murdock series	121°59’57.033”	37°18’12.121”
Pleasanton series	121°40’54.70”	37°10’05.26”
San Ysidro series	121°34’24.356”	37°6’8.045”
Wilson School Pit1	121°57’20.55”	37°20’38.73”
Wilson School NE side	121°57’27.745”	37°20’40.488”
Wilson Sch. near Benton	121°57’28.084”	37°20’42.693”
Yolo series	121°33’01.32”	36°57’59.95”
Zamora series	121°42’34.04”	37°10’55.31”
Shoreline 2a	122°4’43.325”	37°25’59.642”
Shoreline 2b	122°4’43.325”	37°25’59.642”
Shoreline 4a	122°5’2.5”	37°25’50.398”
Shoreline 4b	122°5’2.5”	37°25’50.398”
Shoreline 7a	122°5’25.736”	37°25’39.108”
Shoreline 7b	122°5’25.736”	37°25’39.108”
Shoreline 8a	122°5’25.378”	37°25’32.021”
Shoreline 8b	122°5’25.378”	37°25’32.021”
Shoreline 10a	122°5’36.903”	37°25’45.185”
Shoreline 10b	122°5’36.903”	37°25’45.185”
Villages 1	121°45’2.701”	37°17’27.68”
Villages 4	121°44’41.241”	37°17’19.985”
Villages 6	121°45’13.852”	37°17’18.348”
Villages 7	121°44’37.249”	37°17’30.72”
Villages 10	121°45’4.537”	37°17’3.012”

Ten of the thirty samples were taken from the Shoreline golf course (Figure 1.4). These locations were chosen with the help of an EC map constructed from data provided by Florence Cassel at California State University Fresno (Figure 1.5). The nature of the site, a golf course built on transported materials from various sources overlaying a municipal waste site, precluded any prior soils information for the area. The EC map was used to determine a sampling scheme aimed at maximizing the variability in physical and chemical characteristics of the samples. A subset of locations was then determined *in situ* by observation (for example approximating soil texture by hand). Five locations from the Shoreline location were chosen and samples were taken from each location at 0-6 inch and from 6-12 inch depths. The Shoreline golf site was the only area where samples were taken below a 6 inch depth. Five of the thirty samples were taken from the Villages Golf and Country Club (Figure 1.6). Like the Shoreline course, a sampling scheme was constructed prior to the sampling date and a subset of those locations was determined by *in situ* observations.

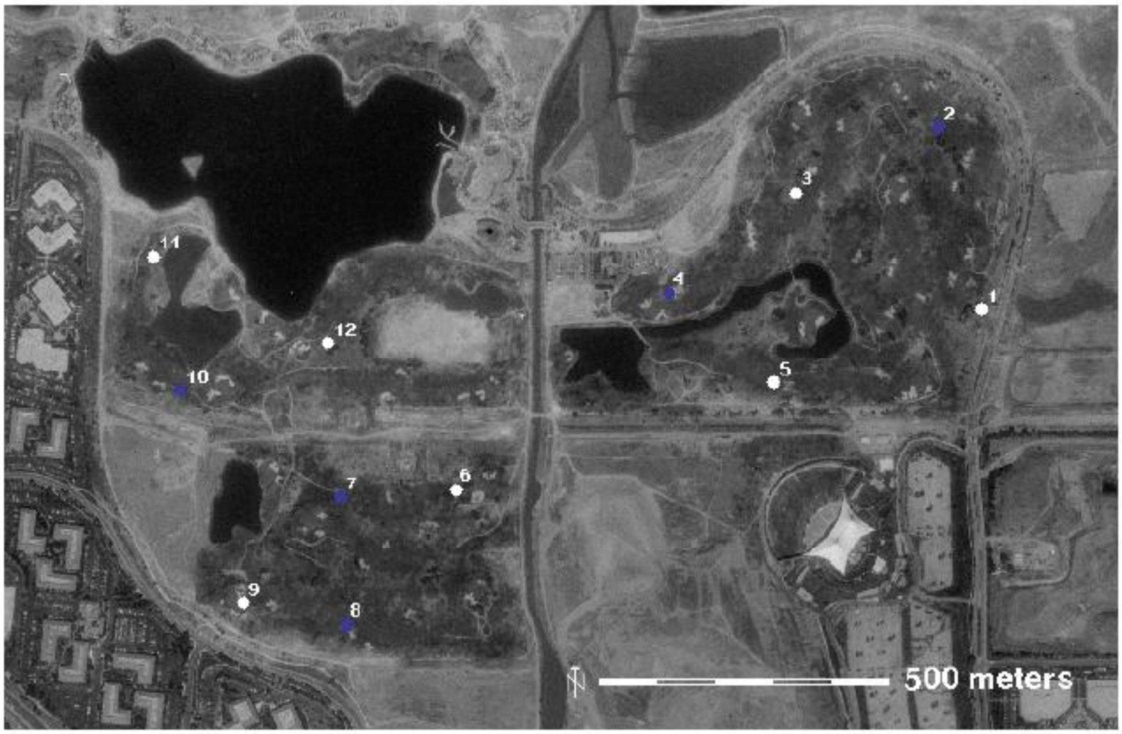

Figure 1.4: Possible sample locations on the Shoreline golf course. The blue points represent those that were actually sampled.

2.2 Sample preparation

Roughly three kilograms of each soil was collected by carefully removing the vegetation and sampling to the specified depth. Additional soil was collected from the Shoreline 2a and 4a locations for use in the grassed column experiment. Samples were transported to Davis in plastic Ziploc bags and dried at 60 °C in plastic tubs. To prepare the soil for the column experiments, the air-dried soil was lightly crushed with a wooden mallet and sieved to < 2 mm.

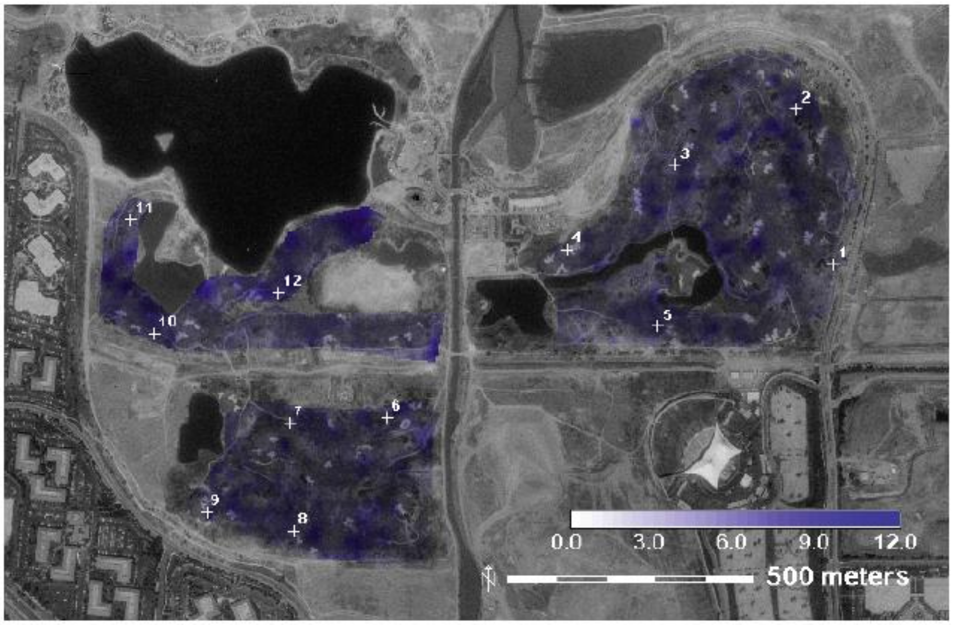

Figure 1.5: A map of the Shoreline Golf Course with interpolated EC data (in dS/m). The EC data was collected by Florence Cassel (California State University Fresno).

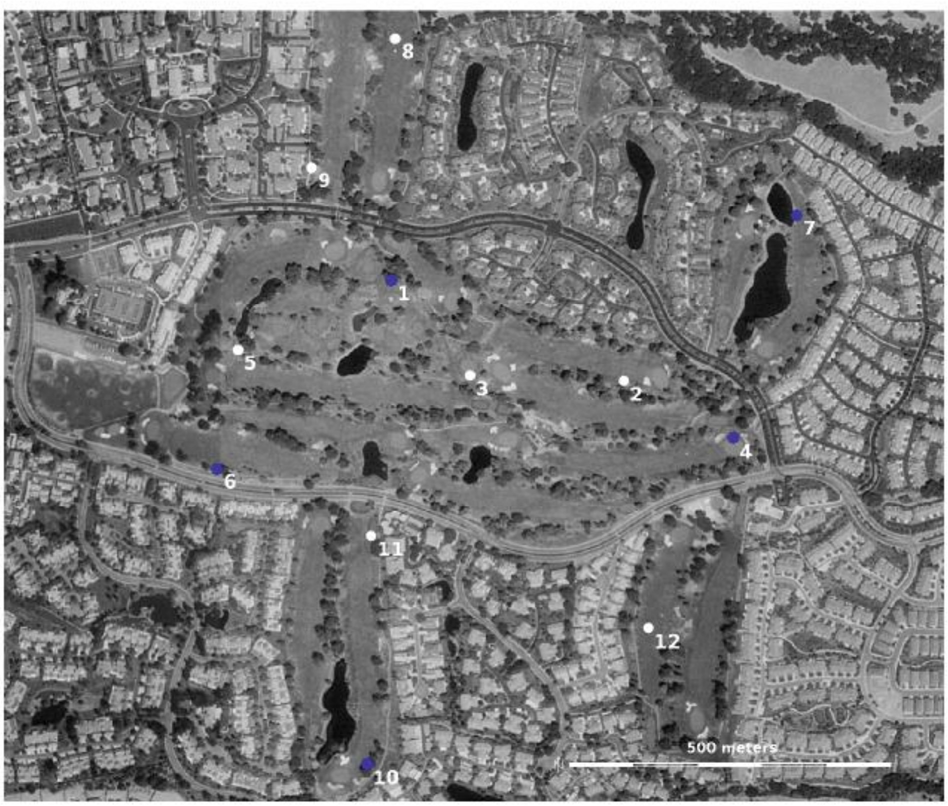

Figure 1.6: Possible sample locations on the Villages golf course. The blue points represent those that were actually sampled.

2.3 Measuring Soil Characteristics

To determine soil physical and chemical properties relevant to hydraulic behavior, several analysis were run in accordance with standard Natural Resources Conservation Service (NRCS) methods. Soil particle size distribution was measured both on a mass basis by pipette analysis (Soil Survey Staff, 2004) and on a volume basis using a Coulter LS-230 laser granulometer (Table 3.1). Cation exchange capacity (CEC) was determined using a modified version of method 5A8c (Soil Survey Staff, 2004) in which KCl was used to extract ammonium from the exchange complex and ammonium concentration was found using spectrophotometry. Base saturation was determined using method 5C1 (Soil Survey Staff, 2004). Saturated paste extracts were collected (method 8A) in order to determine pH and EC (Soil Survey Staff, 2004). Soil moisture percent was measured using the oven-dry method at 105 °C and calculating gravimetric water content. Coefficient of linear extensibility (COLE) was determined using a method developed by Schafer and Singer (1976). Total C and N were determined by combustion-GC (Carlo Erba NC1500). The inorganic carbon content was determined using a method developed by Mike Machette and modified by Gil Eshel (Machette, 1986) where hydrochloric acid combines with carbonates to produce carbon dioxide gas (Equation 2.1). Selected physical and chemical values are in Table 3.2.

$$CaCO_3 + 2HCl \Leftrightarrow CaCl_2 + CO_2 + H_2O \qquad (2.1)$$

2.4 Hydraulic Conductivity Using Soil Columns

2.4.1 Preparing Soil Columns

Soil columns 8.5 cm diameter and 5.5 cm deep were hand packed with 300 g of air-dry soil to a target bulk density of 1.35 g/cm^3. Three replicate columns were run for each soil using each SAR. Nine columns were run for each of the thirty soil samples. The water qualities applied to the soils were combinations of SAR 3, 6, or 12 and EC 50, 10, 5, 1, 0.5, 0.1, and 0 dS/m. The EC series corresponds to solution concentrations of 500, 100, 50, 10, 5, 1 and 0 mmol(+)/L. A set of solutions for three column replicates would then be the dilution series with the SAR held constant. Once the soils were packed, CO_2 was passed through the column for two hours at less than 5 psi to displace any entrapped air (Figure 2.1).

> “Displacement of soil-air with CO_2 before wetting is simple and brings about the complete saturation of a soil in a very short time, allowing the permeability of the saturated soil to be determined without waiting several days for the entrapped air to dissolve.” Christiansen et al. (1945).

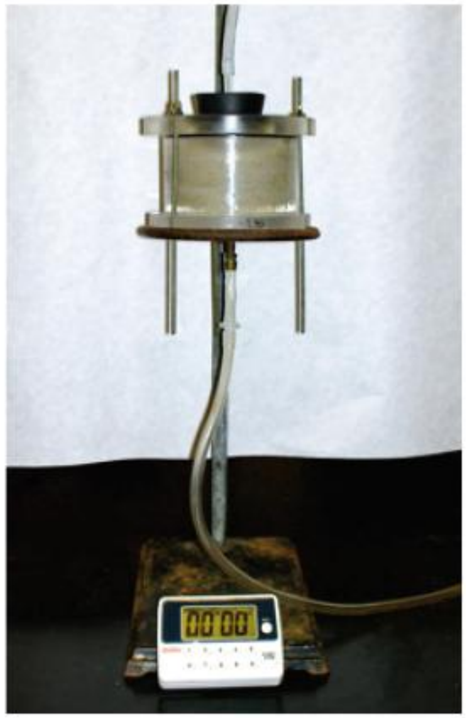

Figure 2.1: CO_2 saturation of a soil column.

Once the column was saturated with CO_2, it was wetted from below by capillary action and low pressure with the 50 dS/m solution for any given SAR. Solutions were applied using a one-liter constant head device called a Mariotte bottle. Two Mariotte bottles were connected to the top of a column using a Y connector and plastic tubing. While solution was running, only one side of the Y valve was open. When approximately 1 L of that solution had passed into the column, the previously closed side of the Y connector was opened, and the previously opened side of the Y valve was then closed. This allowed for a continuous solution application and avoided any disruption in the data collection. While one solution was being applied, the now empty Mariotte bottle was refilled with the next solution in the sequence. Figure 2.2 shows the column and Mariotte bottle apparatus.

2.4.2 Measuring Hydraulic Conductivity

The hydraulic conductivity of a soil can be calculated using a rearranged version of Darcy's Law (Equation 2.2) given a flux and the head gradient. In this equation, K is the saturated hydraulic conductivity (a constant for a given soil under a particular water quality) usually measured in cm/s. The flux, q, is a volume moving through an area per unit time (cm/s). In this case, the area used in the flux calculation is the area of the soil column. L is the length (height) of the soil in cm and ΔH is the change in head (a measure of potential using cm of water) across the length of the soil (also in cm).

$$K = q * \frac{L}{\Delta H} \tag{2.2}$$

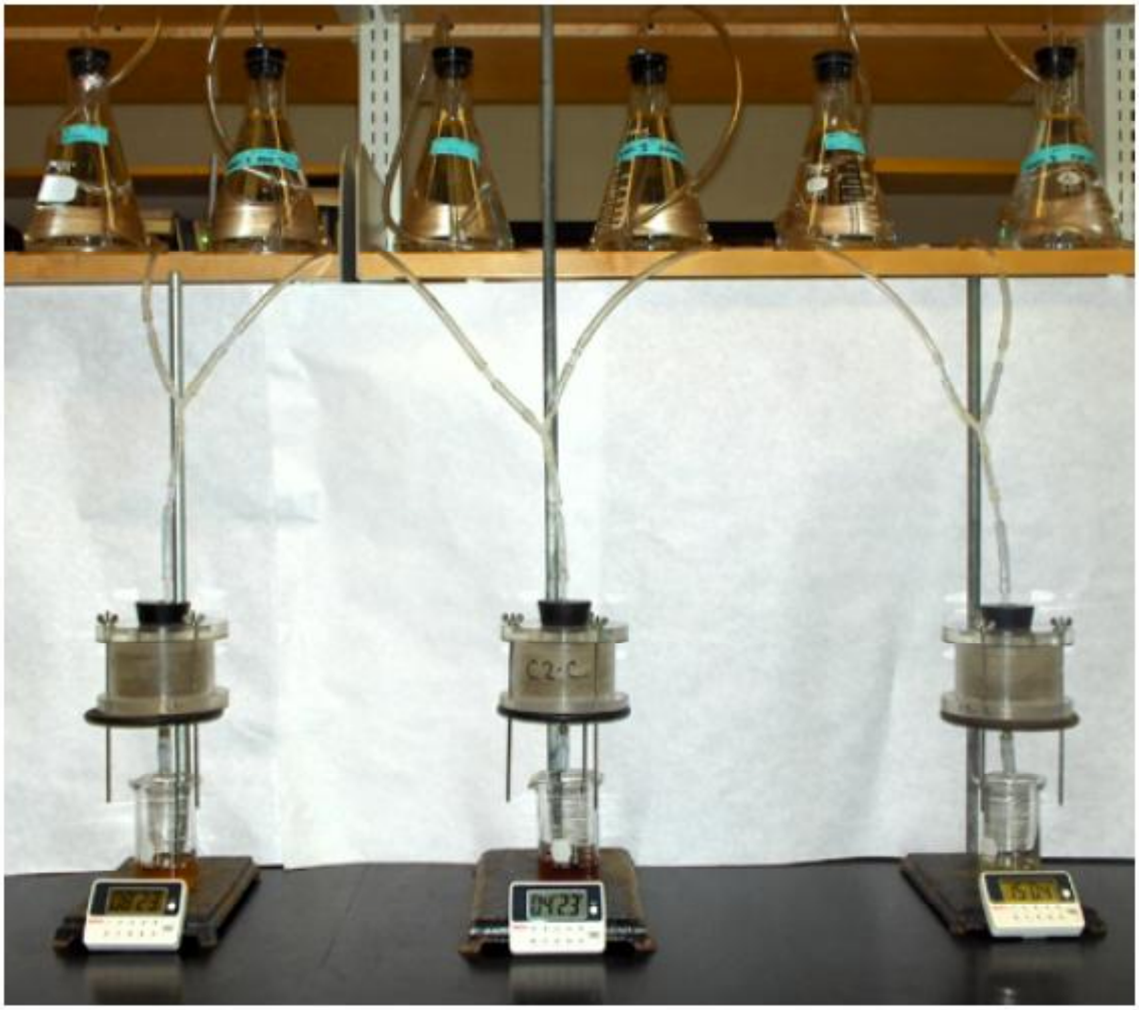

Figure 2.2: Column and Mariotte bottle apparatus.

To calculate K, the flux and the head gradient must be measured. To obtain a steady state flux value for any water quality, the volume of leachate from the column was measured using a fraction collector (Figure 2.3).

Because we used a rearranged version of Darcy's law (Equation 2.2), we must also use the reciprocal of the head gradient in calculating Ksat. Thus, we measured the height of the packed soil in the column and divided it by the change in head across the soil. ΔH is calculated using Equation 2.3 where H_{T2} is the total head at point 2 (the top of the soil) and H_{T1} is the total head at point 1 (the bottom of the soil) (Figure 2.4).

$$\Delta H = H_{T2} - H_{T1} \quad (2.3)$$

To find H_{T2}, we use Equation 2.4 where H_{g2} is the gravitational head (L) at point 2 and H_{p2} is the pressure head (X) at point 2 (Figure 2.4).

(a) A picture of one of three fraction collectors used in this experiment.

(b) A close-up picture of a column output and the top of a fraction collector.

Figure 2.3: Fraction collector used to collect column leachate samples.

$$H_{T2} = H_{g2} + H_{p2} \tag{2.4}$$

To find HT_1, we used Equation 2.5 where Hg_1 is the gravitational head (0 because gage pressures are used assuming 1 Atm reference level) at point 1 and Hp_1 is the pressure head (-Y) at point 1 (Figure 2.4).

$$H_{T1} = H_{g1} + H_{p1} \tag{2.5}$$

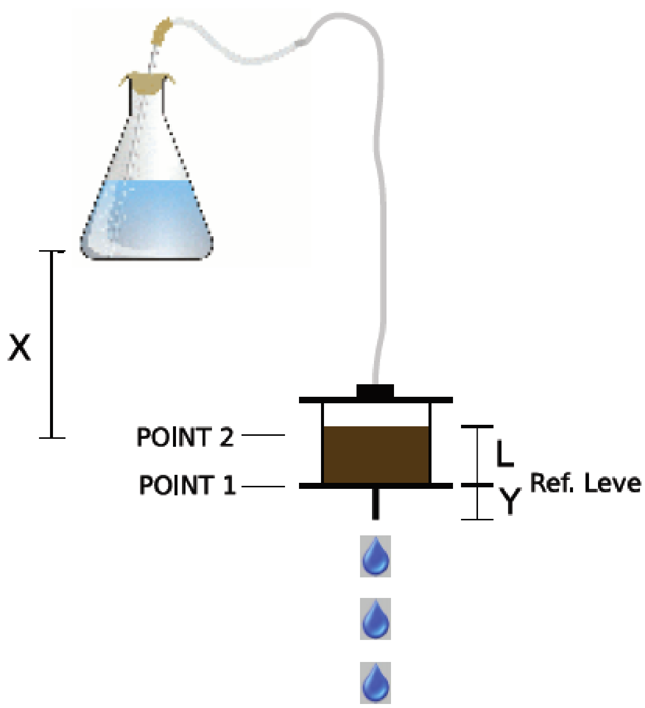

Figure 2.4: A diagram of a column/Mariotte apparatus used in the constant head method.

2.4.3 Statistical Methods Non-grass Columns

Once the steady-state saturated hydraulic conductivity (Ksat) data were collected for each soil at each water quality, the observations were organized into a graphical matrix. The mean soil response for each SAR/solution series application of the three column replicates for each soil was calculated. To test the significance of water quality treatments, a linear mixed effects (LME) model was run for SAR and EC across all soils. The LME model is used to evaluate the relationship between a response variable (in this case Ksat), and one or more predictor variables (SAR and EC). UC Davis statistics consultant Jerome Braun suggested this method, because it is well suited for longitudinal data (an experiment in which subsequent treatments are applied to the same object). In this case, multiple solution concentration treatments were applied to the same soil column at a particular SAR. In addition, the LME model takes into account expected random variation associated with physical differences between replicates.

When comparing relative numbers that are not normalized to the same value, it is not appropriate to run a generalized ANOVA for all values. Thus, to analyze the relative data, an ANOVA was conducted on results from each soil individually to determine significance of log concentration and SAR.

Box and whisker plots were constructed for each soil (Figures 6.3.1-6.3.30) to be able to observe variability in the data. This type of plotting environment was chosen because it shows the smallest observation, the lower quartile, the median, the upper quartile, and the largest quartile. In addition, the graphs indicate any existing outliers.

Two methods were used to further investigate the hydraulic behavior of the soils. In both methods, the data analyzed were the relative hydraulic conductivity where for every soil, at each solution concentration, the column replicates for all sodium adsorption ratios have been averaged to one mean value. In the first method, the PAM (partitioning around medoids) algorithm (Kaufman and Rousseeuw, 2005) was applied to the data, which grouped the soils into categories based on relative hydraulic conductivity behavior. In the second, soils were grouped according to the concentration at which a 15% reduction occurs. This is the Quirk and Schofield (1955) threshold. The PAM clustering method aims to minimize the dissimilarity within groups of data and maximize the dissimilarity between groups of data. Dissimilarity between points of data is determined by the Euclidean distance between points in six dimensional space, because there are six solution concentration treatments. For each cluster (or group of data points) there is a central data point termed the *medoid* that is representative of the group. Specifically, this point is the "object of the cluster for which the average dissimilarity to all other objects of the cluster is minimal." Thus, the points of a cluster (excluding the central point) are said to be partitioned around its medoid.

2.5 Hydraulic Conductivity Using Grassed Soil Columns

2.5.1 Preparing Grassed Soil Columns

Similar to the soil columns described above, the columns used for the grassed-soil experiment consisted of disturbed, crushed and sieved soil packed by hand into 19 cm diameter, 5.5 cm deep columns (Figure 2.5). Six columns were packed with the Shoreline 2a soil, and six were packed

Figure 2.5: One of the columns used in the grassed-column experiment. This column has just had fresh seed spread on the packed soil surface to begin germination.

with the Shoreline 4a soil. Approximately 1.8 Kg of soil were packed into each column to a bulk density of 1.35 g/cm^3.

'Wilbur Ellis Select, perennial ryegrass overseed blend' grass-seed was used in these experiments. It was recommended and supplied by the UCD campus turf manager. The mixture contained 48.86% Covert perennial ryegrass, 24.43% Whitney perennial ryegrass, and 23.13% Socrates perennial ryegrass. Each column was planted with 10.0 g of seed. The seed was wrapped in cheesecloth and allowed to soak in distilled water overnight to encourage germination. A 75 watt fluorescent bulb was placed overhead to provide warmth and light. After the seeds began sprouting (about 2 days), they were transferred to the columns and spread evenly on the soil surface (Figure 2.5). Columns were then placed in a growth chamber set at 25 °C and 45% humidity. The grass was watered every few days until growth was established (Figure 2.6).

Figure 2.6: Grassed soil columns once growth was established.

Once growth was established (about two months), the grass was cut down to the soil surface and columns were run using the same methods applied to the regular (un-grassed) columns except that only solutions of SAR 3 and 12 were applied. Steady state fluxes for each dilution in each series were measured along with the head gradients and used to calculate the saturated hydraulic conductivities. After the flux values were recorded, the finished columns were retained in order to collect the roots for additional analysis.

2.5.2 Root Collection and Measurement

A metal cylinder (area = 57.42 cm^2, height = soil height in column) was used to extract 3 core sub-samples from each packed, grassed-column. Roots were extracted by gently washing the soil from the core samples into a fine sieve. Washed roots were placed into labeled specimen cups and covered with a 5% propanol alcohol solution for root preservation. From each core sub-sample, three representative “pinches” were extracted. Each pinch was placed into a propanol solution bath under a microscope where the roots were separated from non-root material (i.e. seed pods, etc.). Both the roots and the non-root material were saved individually for further analysis. The root samples were analyzed using a Comair root scanner (Commonwealth Aircraft Corp., Ltd., Melbourne, Australia) to determine total root length and then air dried at 40 °C and weighed. The non-root material was also air dried at 40 °C and weighed. These data were then used to determine average root length and root mass density for each grassed-column.

2.5.3 Statistical Methods–Grass Columns

To obtain a root length density for roots in each column, the measured root lengths were compared to standards. The Comair root scanner is similar to a record player where the record is a clear, glass disk that holds the roots, and the needle is an image sensor. A point light source is underneath the disk and moves with the “needle” (sensor), from the center of the disk outwards, recording total root length as the disk slowly spins. Fishing line was cut to known lengths (y) , measured on the root scanner (x) and used to make a standard curve (Figure 6.2.1). The linear regression equation produced from the standard data shown in Equation 2.6 had an $R^2 = 0.99$ and a p-value of less than 0.0001.

$$y = 1.235x - 0.114 \tag{2.6}$$

The dried weights of the roots from each representative pinch were analyzed against the weights of the non-root material from the same pinch to determine a relationship between root mass (x) and root length (y) (Figure 6.2.2). Two linear regression equations were compared to find the best root mass to length relationship (Equations 2.7 and 2.8). The two regression equations had comparable R^2 values and goodness of fit tests, but equation 2.8 was chosen because it had the lowest standard error values associated with both the intercept and slope terms.

$$y = 143.262x + 0.3076 \tag{2.7}$$

$$y = 42.280\sqrt{x} - 2.551 \tag{2.8}$$

Root mass density for each grassed-column was compared with a Wilcoxon rank sum test to determine if significant differences existed between soil types (Figure 6.2.3). While seed on all grassed-columns began germination at the same time, the Shoreline 2a columns had two extra weeks of growth while hydraulic measurements were made on the Shoreline 4a columns. Thus, it was important to determine if this had an effect on the mass density of the columns, which could have affected the hydraulic behavior of the soils.

The relative saturated hydraulic conductivity for each grassed column was compared. A linear mixed effects model was used to test the significance of the treatments on the relative saturated hydraulic conductivities of the grassed-columns. To compare grassed-column results with results from the regular-columns, the Ksat values for the grassed columns were averaged across SAR for each soil at each concentration. The range in relative Ksat for all concentrations could then be compared between grassed and regular columns. An ANOVA was used to test for significant differences between the grassed and the regular columns.

Chapter 3

3.0 Results and Discussion

3.1 Soil's Data

The distribution of soil particle sizes from both methods can be seen in Table 3.1 and in the soil texture triangle (Figure 3.1). We met our goal to sample soil horizons with a wide range of particle size distributions. Clay content varied from 7 to 48% on a mass basis and from 2 to 23% on a volume basis. The laser granulometer underestimates the clay content and overestimates the silt in these soils.

Table 3.1: Particle Size Distribution by Two Methods.

Sample ID	Mass %			Volume %		
	Sand	Silt	Clay	Sand	Silt	Clay
Arbuckle	50	34	16	47	45	8
Campbell	12	57	32	18	65	17
Cardoza	31	35	35	43	49	8
Clear Lake	11	66	23	21	62	17
Garretson	63	23	14	56	41	3
Hillgate	38	48	14	46	44	10
Machado	13	39	48	23	60	17
Murdock	36	41	23	44	52	5
Pleasanton	43	42	15	36	53	11
San Ysidro	40	45	16	41	49	10
Wil. Sch. Pit1	43	42	15	55	39	6
Wil. Sch. NE side	49	34	17	49	46	5
Wil. Sch. near Benton	50	37	13	53	41	6
Yolo	43	37	20	39	48	13
Zamora	18	52	30	19	61	19
Shoreline 2a	24	35	40	21	57	22
Shoreline 2b	38	30	32	20	57	23
Shoreline 4a	66	24	10	59	37	4
Shoreline 4b	70	20	10	63	31	6
Shoreline 7a	50	28	22	47	43	10
Shoreline 7b	50	27	23	28	54	18
Shoreline 8a	47	37	15	20	66	14
Shoreline 8b	76	17	7	56	36	8
Shoreline 10a	51	30	19	67	28	5
Shoreline 10b	41	40	20	45	45	10
Villages 1	37	43	20	60	37	3
Villages 4	56	26	18	58	38	4
Villages 6	53	30	17	71	27	2
Villages 7	60	24	17	79	19	2
Villages 10	53	30	17	60	33	7

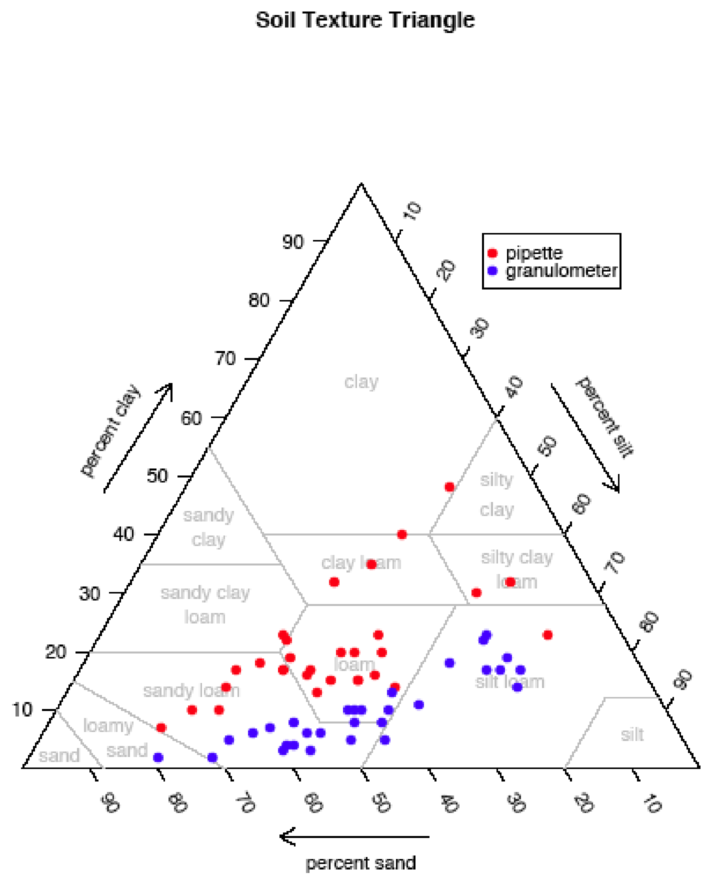

Figure 3.1 Particle size distribution by pipette (mass percent) and laser granulometer (volume percent) methods.

Soil pH and electrical conductivity also ranged widely (Table 3.2). Most soils had a pH above 8.0, indicating a natural accumulation of calcium, magnesium and sodium. This is not unusual for California. Electrical conductivity, a measure of soluble salts, indicated that Shoreline 10a and 10b and the Villages 6, 7, and 10 are "naturally" saline. Naturally is put in quotes because the salinity could very well be a function of the irrigation regime. This should be considered when interpreting the column results. The coefficient of linear extensibility (COLE) also ranges widely from 0.01 to 0.10. A COLE below 0.03 is considered a low shrink-swell and a COLE above 0.09 is considered a very high shrink-swell. Soils with moderate COLE (0.03 to 0.06) have sufficient shrink-swell to be problematic under irrigation.

Cation exchange capacity is a function of clay and organic matter content and varies from soil to soil. Less than 50% of the soils have measurable free carbonate in the horizons sampled. The presence of carbonate tends to maintain a higher EC than those soils without carbonate and can help buffer the effect of low EC irrigation water.

Table 3.2: Select chemical and physical properties of sampled soils.

Sample ID	pH (1:1 water)	EC (dS/m)	COLE	CEC (cmol (+)/Kg soil)	CO_3 (Kg /Kg soil)	Total N	Total C
						(%)	
Arbuckle	7.3	0.05	0.039	11.6	BDL*	0.21	2.42
Campbell	8.2	0.74	0.045	22.1	BDL	0.22	2.67
Cardoza	8.0	1.21	0.099	30.2	0.02	0.34	5.31
Clear Lake	8.1	0.84	0.07	26	BDL	0.20	2.38
Garretson	8.0	1.79	0.039	29	BDL	0.52	9.19
Hillgate	6.5	0.86	0.017	12.1	BDL	0.14	1.99
Machado	8.2	0.65	0.105	29.1	0.03	0.35	5.04
Murdock	7.9	1.31	0.068	34.5	BDL	0.46	8.67
Pleasanton	8.1	0.62	0.041	9.3	BDL	0.10	1.10
San Ysidro	7.5	1.10	0.044	11.4	BDL	0.12	1.60
Wil. Sch. Pit1	6.7	0.30	0.026	17.9	BDL	0.26	4.97
Wil. Sch. NE side	7.6	1.71	0.043	27.6	BDL	0.29	6.31
Wil. Sch. near Benton	6.3	0.35	0.028	17	BDL	0.22	3.76
Yolo	8.0	0.46	0.049	15.5	BDL	0.13	1.45
Zamora	7.8	2.31	0.047	16.7	BDL	0.12	1.37
Shoreline 2a	8.5	2.64	0.066	21.5	0.06	0.20	3.30
Shoreline 2b	8.3	2.79	0.058	15	0.11	0.12	2.78
Shoreline 4a	8.0	1.56	0.041	9.2	0.02	0.19	3.49
Shoreline 4b	8.0	0.92	0.024	10.5	0.02	0.07	1.27
Shoreline 7a	8.3	2.23	0.051	14.4	0.1	0.20	4.45
Shoreline 7b	8.6	1.19	0.05	14.4	0.1	0.11	3.20
Shoreline 8a	8.5	1.85	0.043	10	0.04	0.24	2.89
Shoreline 8b	8.4	1.10	0.014	6.5	0.02	0.04	1.11
Shoreline 10a	8.0	5.89	0.042	12.9	0.01	0.35	4.45
Shoreline 10b	8.0	7.61	0.04	10.9	0.02	0.08	1.23
Villages 1	8.2	2.56	0.065	17.2	BDL	0.43	4.35
Villages 4	8.0	2.58	0.03	15.9	BDL	0.39	3.86
Villages 6	7.8	4.14	0.068	20.3	BDL	0.46	4.74
Villages 7	7.6	12.78	0.044	15.3	BDL	0.57	5.64
Villages 10	8.1	5.70	0.034	12.9	BDL	0.43	4.35

*BDL = below detectable limit.

3.2 Regular Soil Columns

Relative Ksat for the replicate columns at each SAR for each soil is in the appendix Figures 6.3.1 through 6.3.30. The following discussion is based on a summary of those data. Figure 3.2 shows the saturated hydraulic conductivity for all soils. Each axis is on a log scale to enable viewing all soil responses. When viewed on a regular arithmetic scale, much of the data is not visible due to the variation in hydraulic conductivities from soil to soil. Figure 3.3 shows the data from Figure 3.2 that has been normalized to produce relative saturated hydraulic conductivities for each soil. Relative saturated hydraulic conductivity at each SAR was calculated by dividing the steady-state Ksat values for each leaching solution by the Ksat value collected from the 50 dS/m

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TIFF (LZW) decompressor
are needed to see this picture.

Figure 3.2 Saturated hydraulic conductivity for 30 samples.

solution. Figure 3.3 shows the concentration (x axis) on a log scale but maintains equal area intervals for the relative saturated hydraulic conductivity (y axis) to be able to maximize data visualization.

Because of the nature of soil columns, (disturbed samples as described in the methods section), the data collected do not reflect the saturated hydraulic conductivity that would be found if measured *in situ* at the locations where the samples were taken. Rather, they provide data that can be used as relative values to find critical thresholds useful for making management decisions. The Ksat data from these columns can be used both to compare soil types (and their respective hydraulic behavior), and to find critical thresholds within a soil under various treatments.

The relative saturated hydraulic conductivity data, (Figure 3.3), indicate that fluid movement through the soils decreases as EC of the leaching solution decreases. Reading the figures from left to right, the EC of the leaching solutions decreases to that of distilled water. The quantitative decrease is different among the various soils because of different clay contents, salinity, and carbonate content.

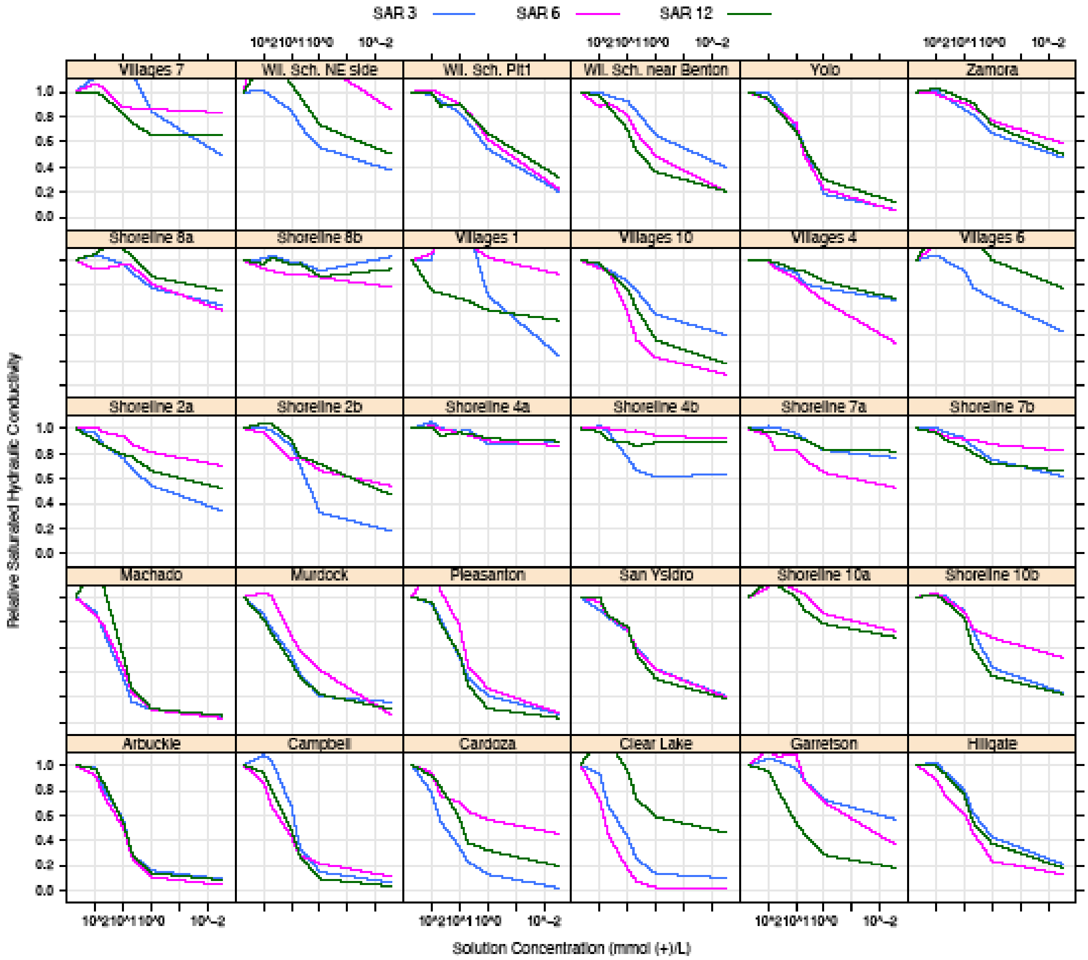

Figure 3.3 Relative saturated hydraulic conductivity for the 30 samples.

These results are less clear in terms of the response of soils to changes in sodium adsorption ratio. Although the LME was only weakly significant for ordered SAR (Table 3.3), it is clear for some of the soils that relative hydraulic conductivities were affected by higher SAR and low EC. For example, five of the thirty soils showed a statistically significant response to the SAR treatments (Table 3.4). This is particularly true for most soils with the application of solutions under 10 mmol(+)/L.

What is somewhat perplexing is that some of the soils at SAR 3 behaved more like soils with higher SAR than did the soils equilibrated at SAR 12. It is interesting to note that in most of the experiments in this field, solutions tested are of SAR 20 or higher. The PAM algorithm applied to the relative data (Table 6.3.1) was used to group soils according to their hydraulic behavior (Figure 3.3

and Table 3.5) and compare the physical/chemical soil properties.

Table 3.3: Significance of terms output from a linear mixed effects model testing individual treatments.

Treatments	Raw Data		Relative Data	
	F-Value	P-Value	F-Value	P-Value
log(concentration)	173.34	<.0001	557.14	<.0001
ordered (SAR)	13.87	<.0001	4.54	0.011
Soil ID	54.92	<.0001	14.03	<.0001

Table 3.4: ANOVA results for soils tested individually (Relative data). Note that significance was determined at a p-value of less than 0.001 where S = significant and NS = not significant.

Soil ID	log Concentration	SAR
Arbuckle	S	NS
Campbell	S	NS
Cardoza	S	NS
Clear Lake	S	S
Garretson	S	S
Hillgate	S	NS
Machado	S	NS
Murdock	S	NS
Pleasanton	S	NS
San Ysidro	S	NS
Wil. Sch. Pit1	S	NS
Wil. Sch. NE side	S	S
Wil. Sch. near Benton	S	NS
Yolo	S	NS
Zamora	S	NS
Shoreline 2a	S	S
Shoreline 2b	S	NS
Shoreline 4a	S	NS
Shoreline 4b	NS	NS
Shoreline 7a	S	S
Shoreline 7b	S	NS
Shoreline 8a	S	NS
Shoreline 8b	NS	NS
Shoreline 10a	S	NS
Shoreline 10b	S	NS
Villages 1	NS	NS
Villages 4	S	NS
Villages 6	NS	NS
Villages 7	NS	NS
Villages 10	S	NS

Equation 3.1 shows the relationship between response and predictor terms, as used in the

LME model. In this case, we are defining saturated hydraulic conductivity as a function of solution concentration, SAR, and the soil type. Log Ksat and concentration were used for two reasons. 1) A log transform compresses the inherent variation found in these terms and 2) the model residuals were more normally distributed, suggesting a better behaving model. The “ordered (sar)” term refers to the conversion of SAR values (a continuous variable) into an ordinal-scale variable (i.e. SAR 6 falls after SAR 3 but before SAR 12). The soil ID represents the specific soil sample.

$$\log(\text{Ksat}) \sim \log(\text{conc}) + \text{ordered}(\text{sar}) + \text{soilID} \tag{3.1}$$

The significance values given by Equation 3.1 can be found in Table 3.3. In this table, the given f-value (an output of the LME model) is used in a statistical test to find the significance between observed differences among means of two or more random samples. This test gives us the p-value, which indicates how well a given predictor variable (concentration, SAR, soil ID) contributes to variation in the response term (Ksat). Significance is determined by establishing a threshold p-value (values <0.01 are commonly used in the natural sciences), where the smaller the p-value, the higher the level of confidence in the effect of a treatment.

Table 3.3 also shows the f- and p-values found for the relative data. The LME model used for these data can be seen in Equation 3.2. This model evaluated Ksat, rather than log(Ksat), because values were normalized between 0 and 1 (and thus the variability in the data were much less).

$$\text{Ksat} \sim \log(\text{conc}) + \text{ordered}(\text{sar}) + \text{soilID} \tag{3.2}$$

Both the raw and relative data were also evaluated using LME models to test for the effects of treatment interactions on Ksat. The models are shown in Equations 3.3 and 3.4 respectively, and their outputs (f- and p-values) are listed in Table 6.3.2.

$$\log(\text{Ksat}) \sim \log(\text{conc}) + \text{ordered}(\text{sar}) \tag{3.3}$$

$$\text{Ksat} \sim \log(\text{conc}) + \text{ordered}(\text{sar}) \tag{3.4}$$

The clusters found within these data fall into four categories. Group 1 included soils that were most affected by solution concentration, group 4 included the soils that were least affected by solution concentration, and groups 2 and 3 fall in between 1 and 4 (Figure 3.4 and Table 3.5). From Figure 3.4, it can be seen that the soils were partitioned around four medoids where group 1 contains soils that were most affected by solutions of low concentrations, and group 4 consists of soils that were least affected by solutions of low concentrations.

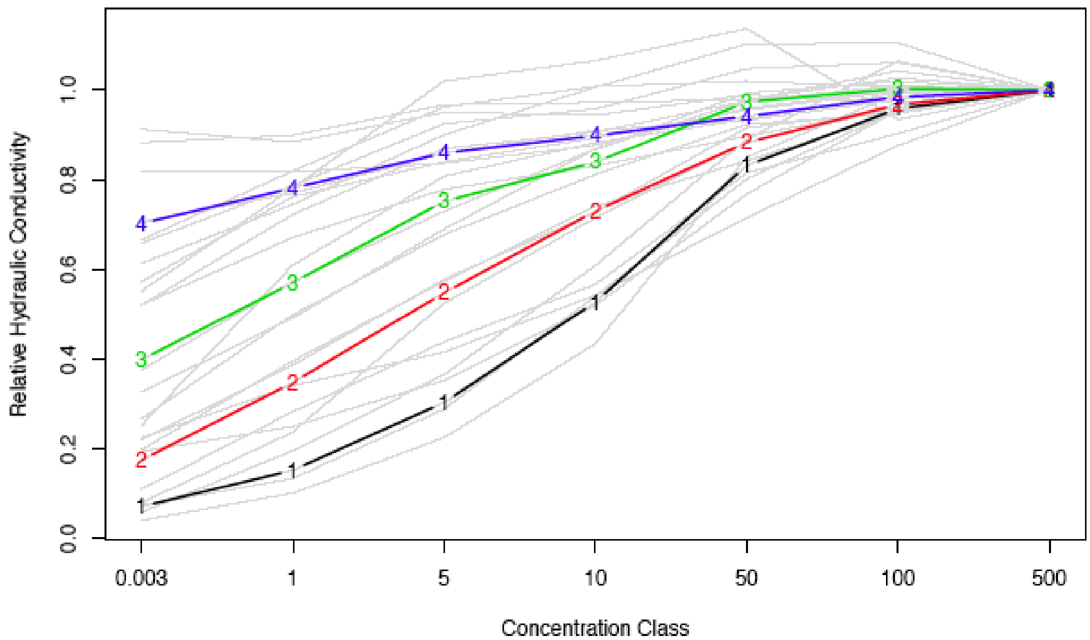

Figure 3.4: A partitioning around medoids algorithm was applied to the relative Ksat data to find four general classes of soils.

Table 3.5: Soils grouped according to a partitioning around medoids algorithm where column 1 contains the soils that were most affected by solution concentration and column 4 contains the soils that were least affected by solution concentration.

1	2	3	4
Arbuckle	Cardoza	Garretson	Shoreline 10a
Campbell	Hillgate	Shoreline 10b	Shoreline 4a
Clear Lake	San Ysidro	Shoreline 2a	Shoreline 4b
Machado	Villages 10	Shoreline 2b	Shoreline 7a
Murdock	Yolo	Wilson School Pit1	Shoreline 7b
Pleasanton		Wilson School near Benton	Shoreline 8a
			Shoreline 8b
			Villages 1
			Villages 4
			Villages 7
			Zamora

Of the soil properties measured, texture and CEC were the soil properties that most correlated with soil hydraulic behavior. A box and whisker plot was constructed for these properties according to the soil groups found by the partitioning around medoids algorithm (Figure 3.5). Comparing these

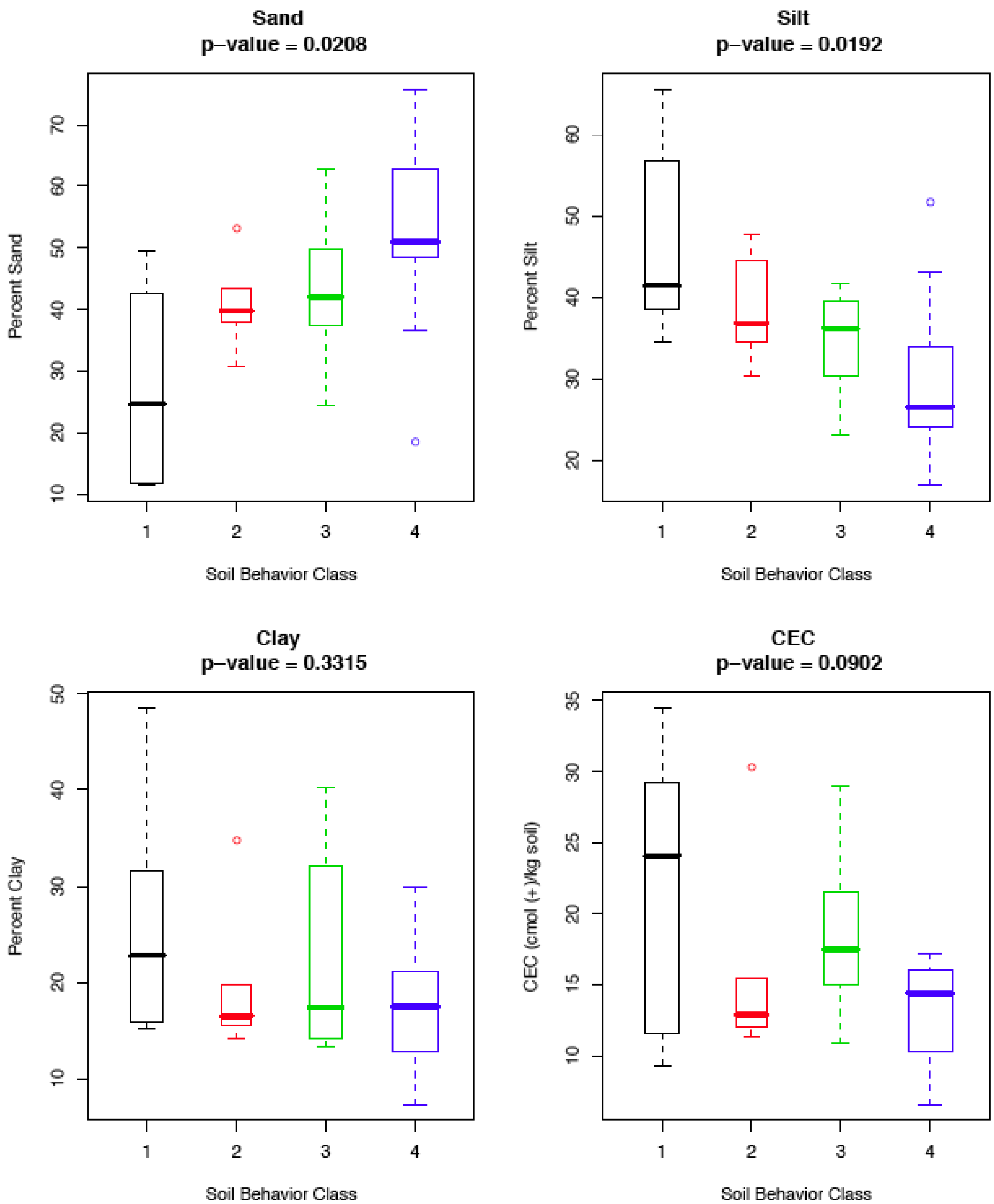

Figure 3.5: Box and whisker plots of soil properties (using the mass % data) according to the soil groups determined by the partitioning around medoids algorithm. In these graphs, the lower horizontal solid bar indicates the smallest observation. The lower box boundary indicates the lower quartile (Q1). The dark horizontal line within the box indicates the median. The upper box boundary indicates the upper quartile (Q3). And the upper horizontal solid bar indicates the largest observation. Any outliers are indicated with an open circle.

groups in Figure 3.5, we see that group 1 has the lowest sand content, the highest silt and clay contents, and highest CEC. In contrast, group 4 has the highest sand content, the lowest silt and clay contents, and the lowest CEC values. Groups 2 and 3 fall in between groups 1 and 4. This trend follows the hypothesis that sandier soils with low cation exchange capacities are least likely to be affected by solution composition. Thus, each will maintain a higher permeability and will be easier to manage. The opposite is true for soils with low sand contents and high cation exchange capacities. From the ANOVA run on these properties, sand content has the highest significance (lowest p-value) in its ability to predict the sensitivity of the soil to solution composition. The distribution of soil textures according to these groups is shown in Figure 3.6.

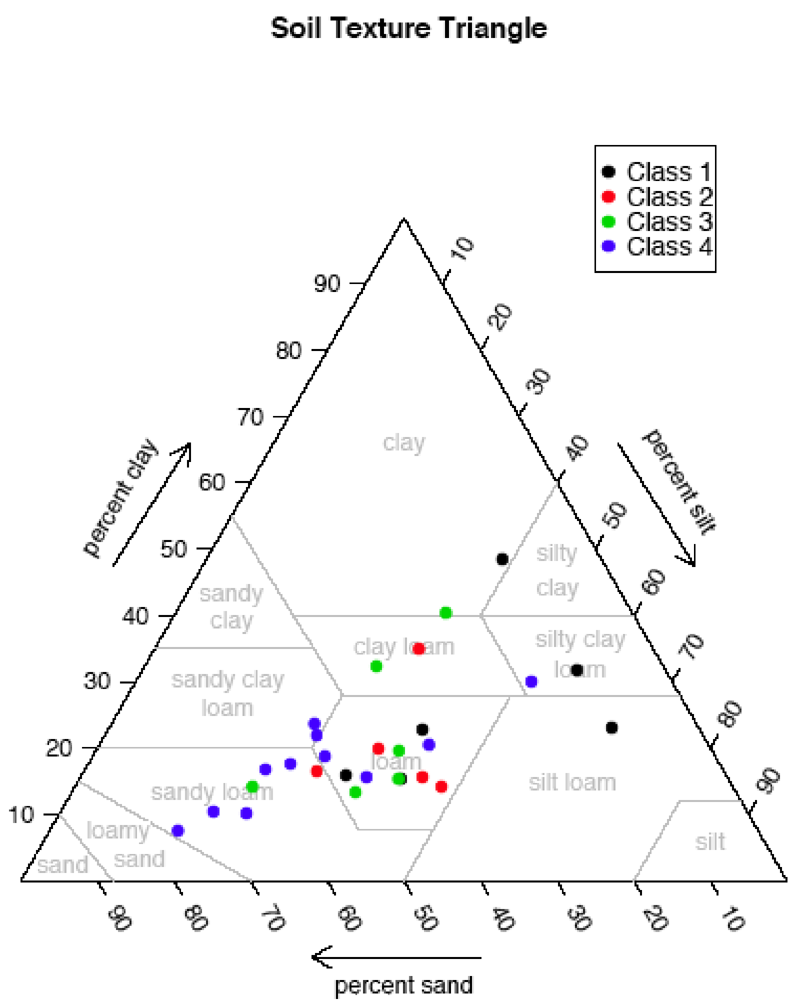

Figure 3.6: A soil textural triangle showing the distribution of soil textures (using the mass % data) by groups formed from a partitioning around medoids algorithm.

Using a different approach, soils were grouped (Table 3.6) according to the solution concentration at which a 15 % reduction in relative hydraulic conductivity occurs (Quirk and

Schofield, 1955).

Table 3.6: Application of the Quirk and Schofield (1955) threshold of a 15% reduction in relative saturated hydraulic conductivity occurs in this project's soils. Each soil is listed at the solution concentration below which the Quirk and Schofield threshold occurs.

Solution Concentration (mmol(+)/L)						
500	100	50	10	5	1	0
	San Ysidro	Yolo	Wilson School Pit 1	Zamora		Villages 6
	Murdock	Wilson School. near Benton	Villages 4	Wilson School NE side		Shoreline 8b
	Machado Clear Lake Cardoza Campbell Arbuckle	Villages 10 Shoreline 2a Shoreline 2b Pleasanton Hillgate	Shoreline 4b Shoreline 10b Garretson	Villages 7 Villages 1 Shoreline 7a Shoreline 10a Shoreline 7b Shoreline 8a		Shoreline 4a

The resulting soil groups can be seen in Figure 3.7. Soils that were sensitive to solution concentration were those that reached the threshold early on in the dilution series. Seven of the thirty soils reached this threshold when the 100 mmol(+)/L solution was applied. Seven soils reached the threshold reduction in Ksat at 50 mmol(+)/L, five were affected with the 10 mmol(+)/L solution, eight were affected with the 5 mmol(+)/L solution, and three soils were not affected until DI water was applied as the percolating solution. Those soils that maintained a relative Ksat above the threshold level until the lowest solution concentrations were applied are the soils that are least sensitive and will be the least difficult to manage. For the thirty soils tested in this experiment, Table 3.6 and Figure 3.7 can help as basic management tools to assess the water quality needed to maintain saturated hydraulic conductivity above the Quirk and Schofield threshold. For example, to maintain relative Ksat above 0.85 (or above a 15% reduction) for the San Ysidro soil, the minimum water quality that may be used as an irrigation source must have an SAR below 12 and an electrolyte concentration above 100 mmol (+)/L. As another example, to maintain relative Ksat above 0.85 for the Villages 10 soil, the minimum water quality used should have an SAR below 12 and an electrolyte concentration above 50 mmol (+)/L.

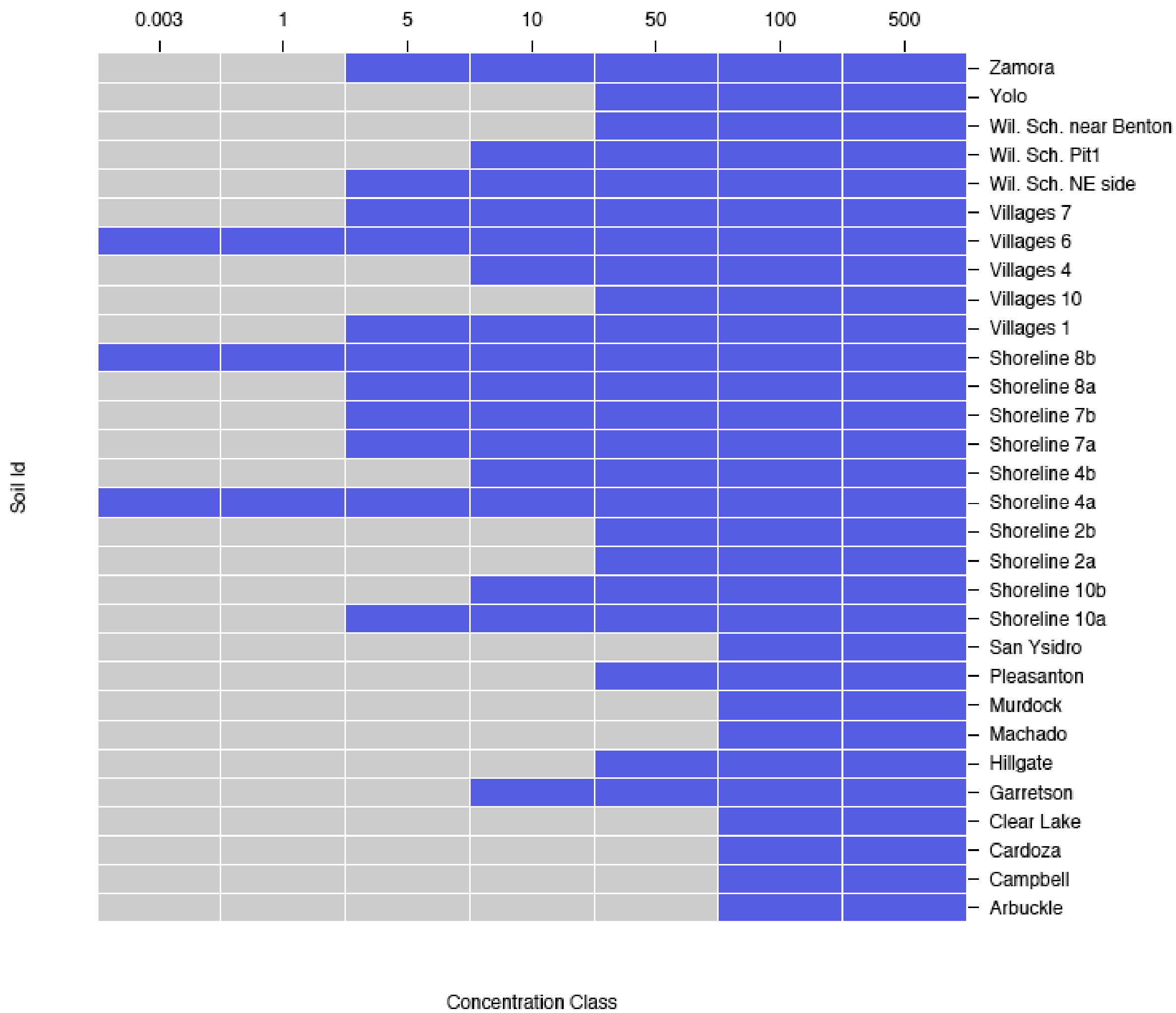

Figure 3.7: This graph indicates the approximate solution concentration at which the Quirk and Schofield (1955) threshold occurs for each soil. For every soil, at each solution concentration, the column replicates for all sodium adsorption ratios have been averaged to one mean value. Blue boxes indicate solution concentrations at which the soil is not affected (i.e. relative Ksat values that are less than a 15% reduction (greater than .85)) and grey boxes indicate solution concentrations at which the soil is affected (i.e. relative Ksat values that are more than a 15% reduction (less than .85)). Thus, the threshold concentration occurs somewhere between the lowest blue box concentration and the highest grey box concentration.

As with the partitioning around medoids method of grouping soils, box and whisker plots were constructed for the soils grouped by the Quirk and Schofield threshold using sand, silt, clay and CEC values (Figure 3.8). The same trend occurs in these plots where the soils that are most affected (for example those that are affected at the 100 mmol (+)/L solution level) have the lowest sand contents, the highest silt and clay contents, and the highest CEC values. Conversely, the soils that are least reactive (for example those that are affected at the 5 or 0 mmol (+)/L solution level) have the highest sand contents, the lowest silt and clay contents, and the lowest CEC values. Using this method to group soils, sand content remains the soil property with the highest significance (lowest p-value) in its ability to predict the sensitivity of the soil to solution composition. The distribution of soil textures according to these groups is shown in Figure 3.9.

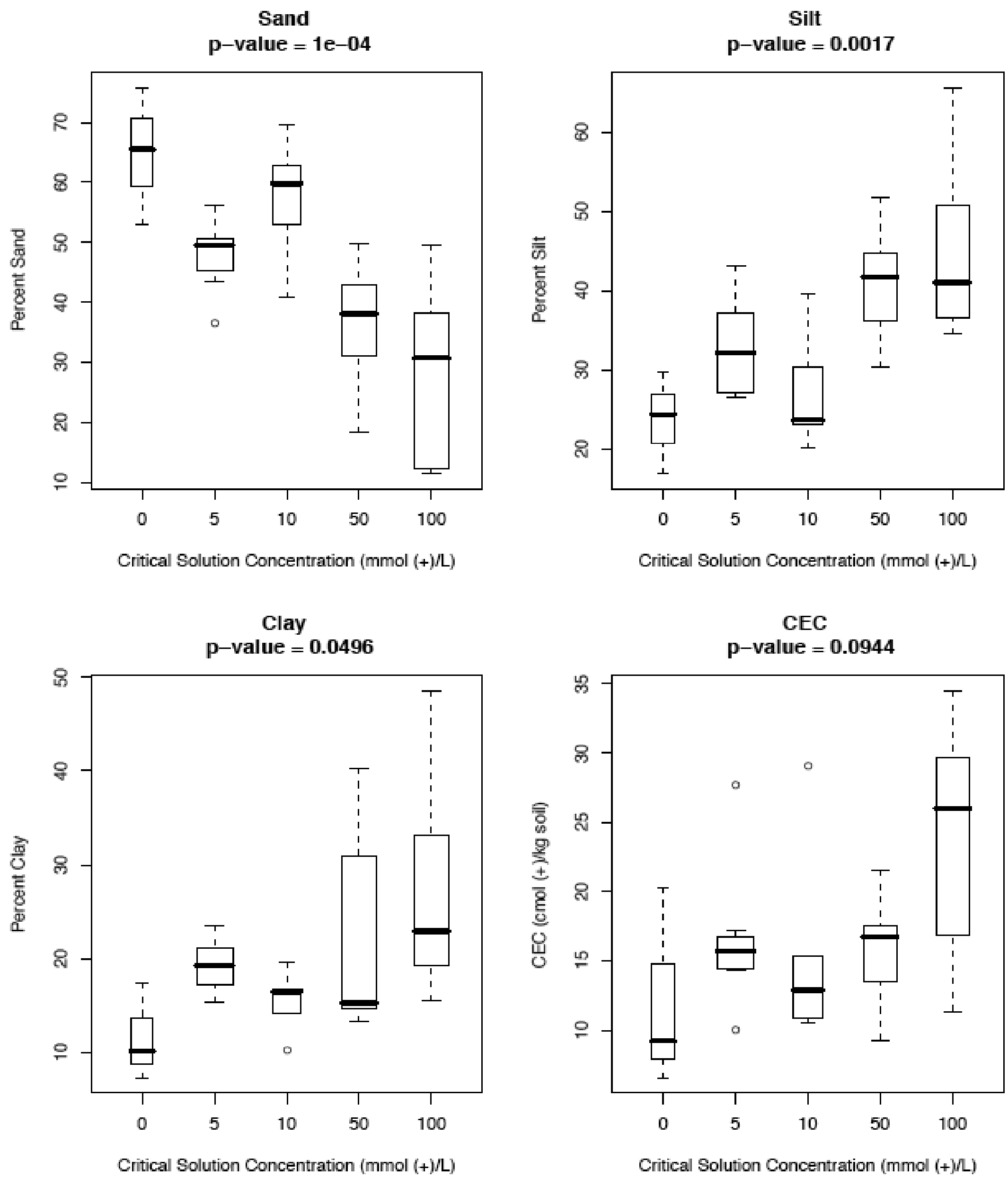

Figure 3.8: Box and whisker plots of soil properties (using the mass % data) according to the soil groups determined by the Quirk and Schofield threshold. In these graphs, the lower horizontal solid bar indicates the smallest observation. The lower box boundary indicates the lower quartile (Q1). The dark horizontal line within the box indicates the median. The upper box boundary indicates the upper quartile (Q3). And the upper horizontal solid bar indicates the largest observation. Any outliers are indicated with an open circle.

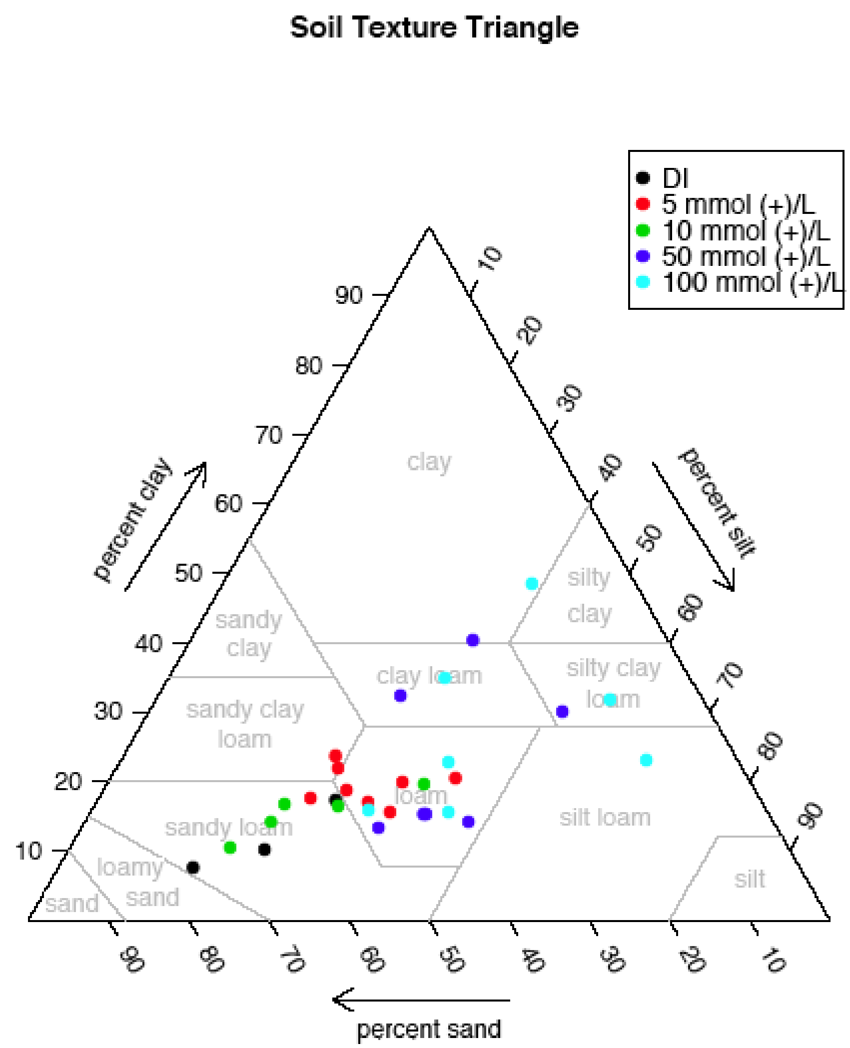

Figure 3.9: A soil textural triangle showing the distribution of soil textures (using the mass % data) by groups formed from using the Quirk and Schofield (1955) threshold.

3.3 Grassed Soil Columns

Because most of the soils tested were sampled from recreational areas (county parks, golf courses, and a school), we were interested in the effects of turf on the saturated hydraulic conductivities of these soils when varying water qualities were applied. The idea we were testing was that soils in columns with grass grown on them would be less sensitive/reactive to varying water qualities compared with the soils in columns without grass. It was thought that the roots from the grass would maintain aggregation within the soil thus minimizing the swelling and dispersion caused by the lower water qualities. These grassed columns were run in the same manner as the regular columns to collect comparable Ksat data, and then the roots were analyzed to determine variations in root growth between soil types.

The relative Ksat data for these columns (Figure 3.10) shows that the Shoreline 2a soil was more affected by the SAR 3 solutions than the SAR 12 solutions.

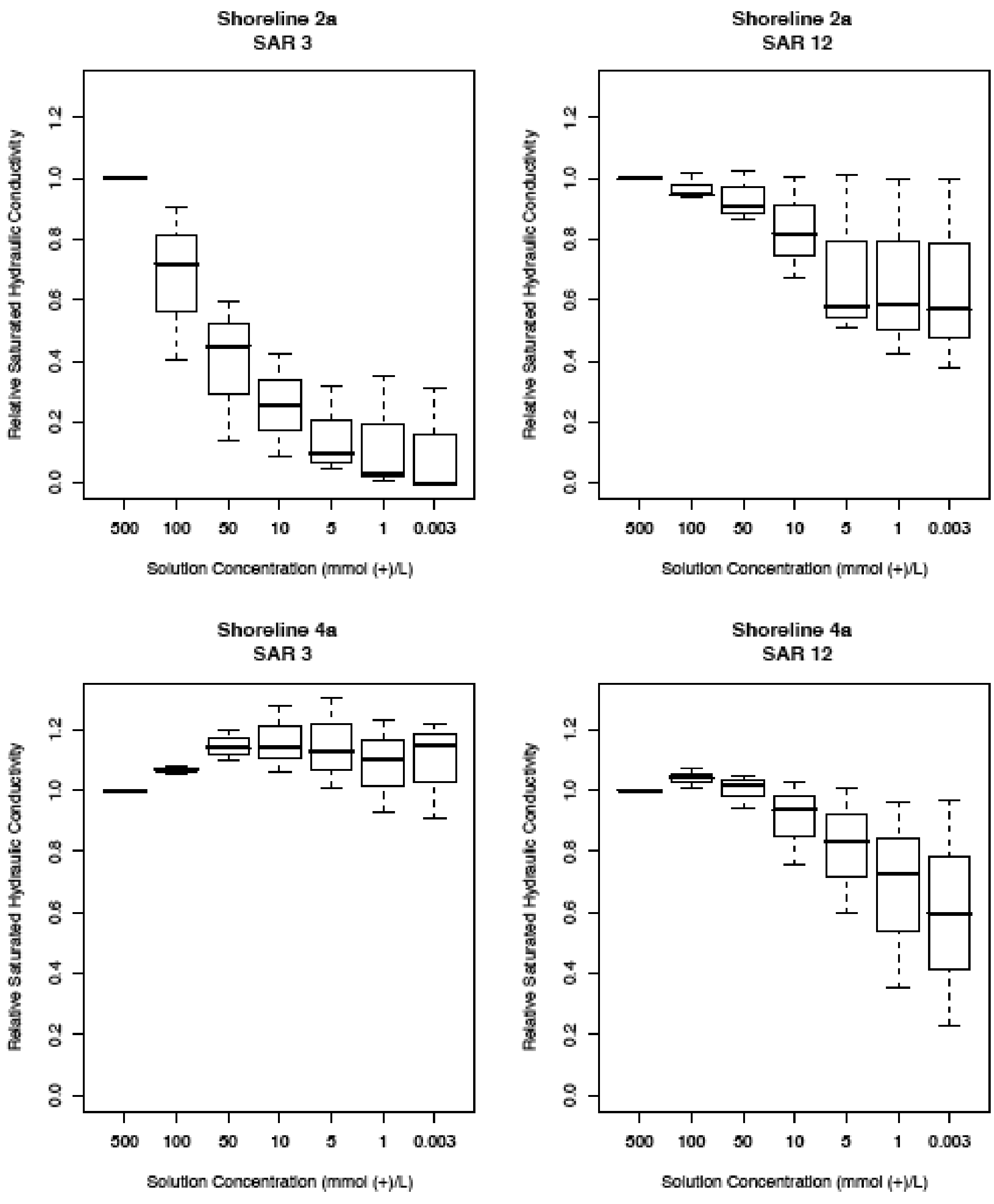

Figure 3.10: Relative Ksat results for the grassed-columns. The lower horizontal solid bar indicates the lowest Ksat. The lower box boundary indicates the lower quartile (Q1). The dark horizontal line within the box indicates the median Ksat. The upper box boundary indicates the upper quartile (Q3), and the upper horizontal solid bar indicates the largest Ksat. Outliers are indicated with an open circle.

This result is contrary to previous studies and to what theoretically should have occurred. Several possible explanations exist. First, because the sample population is so small, it is possible that we cannot draw a definite conclusion about the effect of SAR on grassed columns. Second, because we found little effect of different sodium adsorption ratios under 12 for the regular columns, this probably also applies to the grassed columns. Third, though each column was carefully packed to a bulk density of 1.35 g/cm^3, slight differences in packing may have resulted in varying pore geometries or localized densities allowing for slower or faster permeability. The samples both show a decline in Ksat as the salt concentration of the leaching solution decreases.

The relative Ksat for the Shoreline 4a soil was significantly more affected by the SAR 12 solutions than the SAR 3 solutions (Figure 3.10 and Table 3.7). Because of the texture of this soil, the low CEC, and because there was no significant effect of SAR on the un-grassed columns for this soil,

Table 3.7: ANOVA results for soils of the grassed-columns (soil type tested individually using relative saturated hydraulic conductivity). Note that significance was determined at a p-value of less than 0.01. S = significant and NS = not significant.

Soil ID	log Concentration	SAR
Shoreline 2a	S	NS
Shoreline 4a	NS	S

this result is unexpected. Like the SAR data for the Shoreline 2a grassed columns, this result may be a product of a low sample population and slight differences in packing of the soil. Figure 3.10 also shows that while the Shoreline 2a soil was significantly affected by solution concentration (Table 3.7), the Shoreline 4a soil is not.

The Ksat of the Shoreline 4a sample, in fact, acted as we would have expected all of the soils to react to changes in EC of the leaching solution. The SAR 3 was too low to have an effect on Ksat even at the lowest EC, while the Ksat of the SAR 12 columns decreased as the EC declined.

The test showed that there was a significant difference between the soils at a p-value of less than 0.0001. The Shoreline 4a columns had much higher root mass densities. Root mass density within soil type was then compared using an ANOVA test. The Shoreline 2a root mass density was significant at the 0.05 level with a p-value of 0.0446 while the Shoreline 4a root mass density was significant at the 0.001 level with a p-value of less than 0.0001.

Equation 3.5 shows the relationship between response and predictor terms, as used in the linear mixed effects models for both soils. The results of the test can be seen in Table 3.7. Because of the small sample size in this data set, significance was determined for p-values < 0.01.

$$Ksat \sim \log(conc) + ordered(sar) \tag{3.5}$$

Given these results, to be able to compare these data with those from the regular columns, the Ksat values for each soil, at each concentration were averaged across replicates and SAR. These values were compared with those from the regular columns (Figure 3.11).

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TIFF (LZW) decompressor
are needed to see this picture.

Figure 3.11: A box and whisker plot comparing the range in relative Ksat values averaged over the three SAR for the grassed and ungrassed columns. The lower horizontal solid bar indicates the smallest observation. The lower box boundary indicates the lower quartile, the dark horizontal line within the box indicates the median and the upper box boundary the upper quartile. The upper horizontal solid bar indicates the largest observation. Outliers are indicated with an open circle.

ANOVA was run to find any significant differences in the relative Ksat values between the regular and grassed columns. While there was no significant difference between columns for the Shoreline 4a soil, the grassed columns had significantly lower Ksat values (at a p-value of 0.0003) than the regular columns for the Shoreline 2a soil. These results do not support the hypothesis that soils in columns with grass grown on them would be less sensitive/reactive to varying water qualities as compared with the soils in columns without grass. Without further investigation, it is not evident as to why the grassed columns had lower saturated hydraulic conductivities.

To further visualize the differences between the grassed and regular columns for the Shoreline 2a and 4a soils, their relative Ksat values were graphed against each other to see where they fall relative to a 1:1 (dashed) line. For the Shoreline 2a soil, all points (excluding the 500 meq/L value which will always be 1 on these relative scales) fall below the 1:1 line meaning that the relative Ksat values for the grassed columns consistently fall below those for the regular columns (Figure 3.11). This is consistent with the results given by the ANOVA for this soil. For the Shoreline 4a soil, points fall both above and below the 1:1 line showing no consistent trend. This is also consistent with the ANOVA results given for this soil.

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are needed to see this picture.

Figure 3.12: Graphs comparing the relative Ksat for the grassed and un-grassed columns.

Perhaps the time that it takes for roots to aggregate the soil is much longer than the growth period allowed in this experiment. Further, it could be that the roots preferentially grow in soil pores that would otherwise be flow paths. To better understand the effects of turf on soil saturated hydraulic conductivity, testing a bigger sample population with a larger variety of soil types is required.

The average root mass and root length densities for all columns were measured and recorded to be able to compare these values with the relative Ksat results. Figure 6.3.3 and a Wilcoxen rank sum test show that the Shoreline 4a columns had significantly higher root mass densities than the Shoreline 2a columns. For the Shoreline 2a soil, the grassed columns had significantly lower Ksat values with a p-value of 0.00034. For the Shoreline 4a soil, there was no significant difference in Ksat values between the grassed and regular columns with a p-value of 0.4857.

Comparing the root mass densities with the relative Ksat results for the grassed columns shown in Figure 3.12, the Shoreline 2a columns, with the lowest root mass densities, have the lowest relative Ksat values and that the Shoreline 4a columns, with the highest root mass densities, have the highest relative Ksat values. This indicates that a higher grass density results in higher permeability, except that from comparing the grassed columns with the un-grassed columns we found that the presence of grass results in lower permeability. Thus the higher Ksat values from the Shoreline 4a columns (as compared with the Shoreline 2a columns) must be a result of the coarser texture and lower cation exchange capacity. Again, given the results from the grassed column experiment, testing more grassed columns on a higher range of soil types is recommended to be able to draw more definitive results.

Chapter 4

4.0 Conclusions

The saturated hydraulic conductivity (Ksat) of thirty soil samples was measured with water qualities of varying SAR (3, 6 and 12) and solution concentration (500, 100, 50, 10, 5, 1, and 0 mmol(+)/L). Using a linear mixed effects model and ANOVA, it was found that there were few significant differences in Ksat due to SAR treatments, but that the solution concentration was a highly significant factor in determining Ksat. Ksat declined as the salt concentration, as measured by electrical conductivity, declined. To further analyze the data, Ksat was averaged across replicates and SAR for each soil at each solution concentration. These means were used to group soils by a partitioning around medoids algorithm. Soils were placed into four groups ranging from most sensitive/responsive to least sensitive/responsive to solution concentration. The soils that were the most sensitive to low electrical conductivity (EC) solutions had the lowest sand content and highest CEC. Soils that were the least sensitive to low EC solutions had the highest sand content and lowest CEC.

The soils were also grouped according to the concentration at which the Quirk and Schofield threshold occurs (Quirk and Schofield, 1955). Using this method, the thirty soils fell into five groups ranging from most sensitive to least sensitive to changing water qualities. The most sensitive soils had a 15% reduction in saturated hydraulic conductivity with the application of the 100 mmol(+)/L solution. The least sensitive soils did not have a threshold reduction in saturated hydraulic conductivity until the application of the deionized water. In these groups as well, the soils that were the most sensitive to solutions of lower EC had the lowest sand content and highest CEC, while the soils that were the least sensitive to solutions of lower quality had the highest sand content and lowest CEC.

Grassed columns were prepared for two of the thirty soils and were run in the same manner as the regular columns except that only two sodium adsorption ratios were tested (3 and 12). Using a linear mixed effects model and ANOVA on the relative hydraulic conductivity data showed that the Shoreline 4a soil was significantly more affected by the SAR 12 solutions than the SAR 3 solutions. Conversely, the Shoreline 2a soil was significantly more affected by the SAR 3 solutions than the SAR 12 solutions. Due to the small sample population and the SAR effects on the regular columns, no definite conclusions may be drawn on the effect of SAR (under 12) on the relative saturated hydraulic conductivities of grassed columns. Using the same tests, the Ksat of the Shoreline 4a columns was not significantly affected by solution concentration, while the Ksat of the Shoreline 2a columns were. When these results were compared to the regular columns of the same two soils, there were no significant differences between columns for the Shoreline 4a soil but the grassed columns for the Shoreline 2a soil had significantly lower Ksat values than the regular columns. This suggests that the presence of turf may lower a soil's hydraulic conductivity. To further investigate this result, the root mass densities for the grassed columns were compared. A Wilcoxen rank sum test showed that the Shoreline 4a columns had significantly higher root mass densities than the Shoreline 2a columns. Because the Shoreline 4a soil consistently had higher Ksat values than the Shoreline 2a soil, this indicates that an increase in grass density results in higher saturated hydraulic conductivities. Thus, no definite conclusions can be drawn about the effect of turf on maintaining the saturated hydraulic conductivity of a soil under varying water qualities. Further research on a larger sample population is recommended for more definitive conclusions about water quality and grassed columns.

Questions remain about how these soils will perform under natural conditions where soil structure has not been changed by preparation for laboratory columns and where saturated flow is the exception, not the norm. An additional variable not considered in this study is the effect of rainfall on the soils. Rainfall will remove salts and lower the electrical conductivity, with the potential to further reduce the infiltration and percolation rates during the rainy season. During the irrigation season, additional water will need to be added above the water needed for plant growth to reduce the salt content so that it does not affect plant growth. At the same time, continued use of the treated effluent will require that some salts remain in the soils to maintain infiltration and percolation.

Use of treated effluent with SAR of 5 or more will surely, over time, add sodium to the soil exchange complex. To maintain the soil structure, infiltration rate, and percolation rate for these soils will require removal of the sodium. One option for managing the sodium and EC is to apply gypsum. Gypsum, along with sufficient leaching water, will help to remove sodium from the soil and will maintain the EC so that soil structure is preserved. Gypsum applied during the irrigation season after salt build up begins will have the greatest effect. Continued careful water management, with additional water added to leach salts is necessary to maintain structure and keep soil hydrology optimum.

Chapter 5

5.0 Bibliography

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