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Salinity Management in Avocado Orchards

Abstract

Avocado is one of the most salinity sensitive crops produced in California, but is commonly grown in areas having saline irrigation water (an EC greater than 0.75 dS/m and chloride >100 ppm). Resulting problems associated with high soil salinity and chloride toxicity cause reductions in fruit yield and tree size, lowered leaf chlorophyll content, decreased photosynthesis, poor root growth, and leaf scorching. During recent years, salinity problems with avocado have become increasingly common as the cost for irrigation water has gone up and the availability of low salinity water for agriculture has diminished. This has resulted in the need for improved knowledge on how to reduce soil salinity through proper irrigation management. This article reviews the causes for salt buildup in soils and the effects of chloride toxicity on avocado growth. Cultural practices including rootstock selection, irrigation water quality and timing, EC monitoring, and soil leaching methods are summarized with specific recommendations.

Introduction

Management of salinity in avocado orchards requires careful use of irrigation practices that provide sufficient water while at the same time minimize the accumulation of salts in the upper profile of the soil where the roots are located. There are two aspects of salinity. The first is the effect of total dissolved salts that reduce the amount of water that can be taken up by the roots (osmotic effects), and the second is the effect of specific ion toxicities that occur due to the uptake of chloride and sodium into the plant tissues. Specific ion toxicity caused by chloride causes the obvious symptoms that appear as a foliar burn, but also causes serious problems with poor root growth. Other long term effects of salinity include deterioration of soil structure that is caused by sodium, which leads to poor soil aeration, inhibited root growth, and poor water infiltration. These indirect effects of salinity will further diminish the ability of trees to effectively take up water and nutrients, which leads to a general downward spiral in tree health and productivity. Irrigation management thus requires careful attention to detail to optimize water use efficiency, yields, and production costs. Among the primary factors affecting salinization and chloride toxicity is the irrigation water quality, followed by irrigation and soil leaching practices. Rootstock selection and management of soil biological and physical properties are also integral to maintaining healthy roots that can efficiently extract water and nutrients under saline conditions.

Irrigation Water Quality

While many growers are concerned about the introduction of mineral salts that are carried in composts, manures, and fertilizers, by far the largest input of salt to the soil comes from irrigation water (Branson and Gustafson, 1972). Actual amounts from irrigation water can be calculated from the water quality reports that are provided by local water management districts. In southern California, typical values for total dissolved salts contained in local water sources range from 200 to 500 mg per liter. The total salts are comprised of a mixture of calcium, magnesium, sodium, and potassium as cations, and bicarbonate, sulfate and chloride as anions. At a concentration of 500 ppm, a seasonal application of 4 acre feet of water (~ five million liters), results in the deposition of an astonishing amount of salt – equivalent to 5,420 pounds (~2460 kg) of total dissolved salts per acre per year. Of this quantity, the amount of harmful salts in the form of NaCl are generally held by water blending or by water treatment at 100 mg per liter (100 ppm) for chloride, and an equivalent amount of sodium. Together these two ions at 100 ppm in 4 acre feet of water amount to an application of 2,200 pounds (~1000 kg) of sodium chloride per acre per year.

Management practices to eliminate these tremendous quantities of salt require continual monitoring of the salt levels in the soil and the use of effective leaching practices to push the salts below the root zone. With proper irrigation management, the upper profile of the soil is routinely leached by passing water through the root zone into the deeper soil profile and eventually into the water table where it accumulates in subsurface groundwater. This subsurface water then flows out to the ocean in underground rivers, or is pumped back up again from underground aquifers for reuse, generally becoming more and more salty if additional irrigation water has been imported on to the orchard, and less salty following rains that dilute the salts. Management thus begins with measurement of the salt concentrations in the irrigation water and soil.

The standard way to measure the total quantity of dissolved salts is to measure the electrical conductivity of the water. Salt water conducts electricity, such that as salt levels increase from distilled water (0 conductance) to saline, the conductance increases in proportion to the quantity of salt. The units that are used to measure conductance are deciSiemens per meter, which is abbreviated as dS/m. An EC value of 1 is equivalent to approximately 640 parts per million of salt, but will vary depending on the composition of the ions in the solution. Other common units of measurement are mmho/cm, and mS/cm (1 dS/m = 1000 mS/cm = 1 mmho/cm = 640 ppm). EC measurements are further annotated with a subscript to describe the type of solution that has been measured. The EC of irrigation water is written as EC_{iw}. Similarly, the EC values for a soil water extract and for drainage water are written as EC_{sw} and EC_{dw}, respectively.

In general, the soil water salinity is always greater than the irrigation water salinity. This is due to the evapotranspiration of water that leaves salts behind in the soil as pure water separates from the dissolved salt when water molecules are taken up across the root cell membranes, or when it evaporates from the soil. The only way to remove these accumulated salts is by leaching the soil, using excess water to push the salts down below the root zone. This process results in a gradient of salt concentrations from the soil surface downward through the soil profile. With avocado, approximately 80% of the roots that take up water and nutrients are located in the top 20 cm of the soil, with the majority of the roots occurring in the top 10 cm. Therefore, this upper zone is the most critical for salinity management.

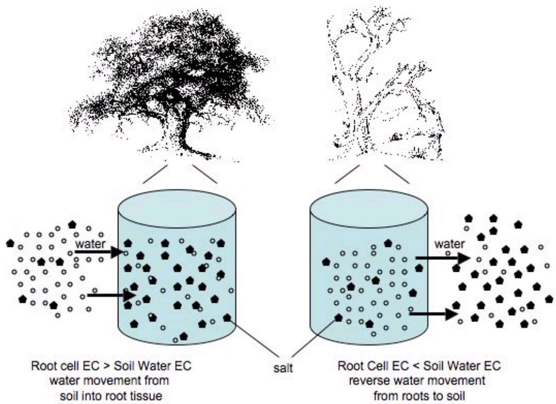


Figure 1. The entry of water into the roots is driven by osmosis in which dissolved salts in the root cells cause less salty water to move from the soil into the roots (a). Conversely, when salt concentrations in the soil are greater than in the root tissues, water moves out of the plant (b). In avocado, this occurs when the soil water electrical conductivity is at 4 dS m^{-1}.

If the soil is not properly leached, the first effect of salt accumulation in the upper soil will be lack of water for the trees; this occurs even though the soil may appear to be wet. This is due to the osmotic effects that prevent the entry of water into the plant roots. As shown in Figure 1, water enters into the roots by osmosis, in which water molecules move along a concentration gradient from low salt to high salt, in essence performing work while diluting the salts. To take up water, the roots accumulate dissolved salts and organic acids that attract or pull water across the membrane into the root tissues.

If the salt concentration is higher in the roots than in the soil, water moves into the roots. On the other hand, when the salt concentration is higher in the soil water than inside the plant roots, the water in the root tissues can actually be sucked back out into the soil. With avocado, results of field studies show that when the EC_{sw} reaches approximately 4 dS/m, avocado trees are no longer able to extract water, even if the soil is water saturated.

Based on experimental data collected by the USDA salinity lab, the salinity of the soil pore water in the rooting zone can be estimated by knowing how much water has leached through the profile (Figure 2). This value is referred to as the leaching fraction. More details on this concept and how it is measured can be found either in the USDA Salinity Handbook and online at http://ucce.ucdavis.edu/files/filelibrary/5049/773.pdf. A graph of the root zone salinity versus the irrigation water salinity shows what leaching fraction is required to maintain a particular root zone salinity (Figure 2). While at first appearance, the leaching fraction appears to be straight forward, one of the practical difficulties is actually measuring when enough water has been applied to obtain the desired leaching fraction. This can only be determined by using soil water monitoring equipment at different depths to see when water has moved through the root zone and has passed beyond 20 cm.

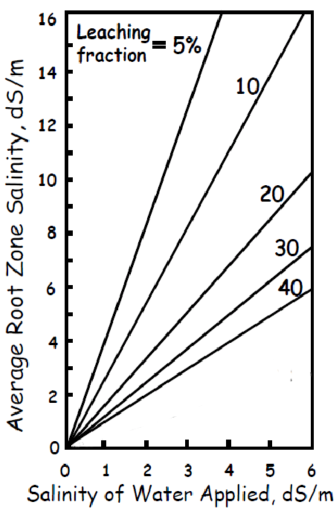


Figure 2. Estimation of percent leaching fraction required to maintain specific root zone salinity. For avocado, the EC_{sw} should be maintained as low as pos-sible as avocado roots cannot extract water above a value of 4 dS/m. If the ir-rigation water has an EC_{iw} of 1, then a minimum leaching fraction of 10% is needed to maintain the average root zone salinity at a value of 2.5. Increasing the leaching fraction to 20% reduces the average root zone salinity to 1.8 dS/m.

To measure the soil water EC, soil samples are taken at incremental depths with a soil coring tube, and a subsample from each depth is mixed with pure distilled water. The most accurate measurements are made with a saturated paste (all of the soil water pores are full), but this requires one or more days to properly prepare and measure. Rapid estimates can be made much more simply by preparing a 1:2 or a 1:5 soil:water suspension; for example by mixing 10 grams of dry soil to 20 mls of water to prepare a 1:2 soil water extract. In the field, this can be done in a matter of minutes using a premarked test tube or jar with calibration marks to indicate specific volumes on the side of the container. Water is first added to a level of 20 ml, and then soil is added until the water level increases to 26 ml (dry soil has a weight of 1.6 g per ml, so 10 grams of soil occupies a 6 ml volume). The salts are allowed to dissolve for a short period by mixing the soil and water, after which the soil is allowed to settle and the salinity is measured with a handheld salinity pen. If the EC of a 1:2 soil water extract is above 1 (equivalent to an EC_{sw} of 2.0), the soil likely needs to be leached to prevent water stress and chloride toxicity. Further, by measuring the EC of the soil at 10, 20, and 30 cm depths, it is possible to quickly determine whether the leaching program has been effective.

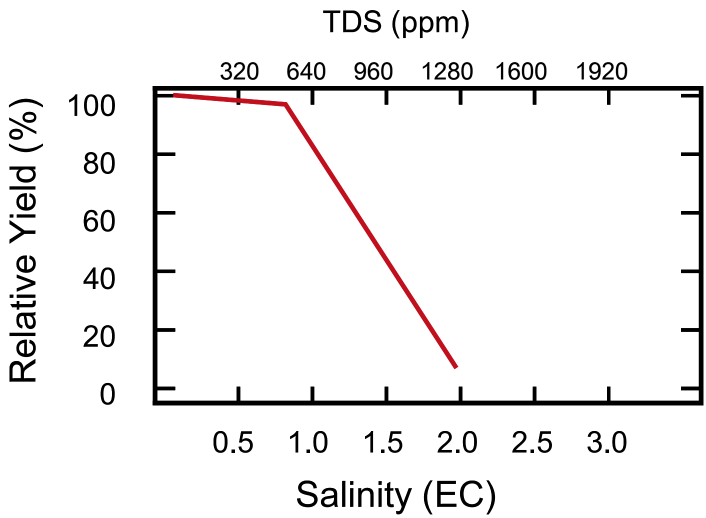


Figure 3. Production function model for avocado yields in relation to soil salinity. Model is based on the irrigation water EC and does not take into account accumulation of salts with inadequate leaching practices. Adapted from Oster and Arpaia 2007.

The relationship between soil salinity measured as EC on avocado yields has been estimated using a production function model developed by Oster and Arpaia (Figure 3). The input data for this model are based on results from a multiyear study at Covey Lane (Oster et al. 2007). These data show that avocado yields are reduced by 65% for each EC unit increase above the threshold of 0.6 dS/m. By comparison, most irrigation water in southern California has an EC of 1 (~640 ppm TDS), which indicates even good quality water contains enough salt to reduce potential yields by 30%.

Chloride Toxicity

The second problem associated with soil salinity is chloride toxicity. Researchers in Israel have shown that chloride is a major limiting factor for root growth (Lahav 2003), and propose a rule of thumb in which there is a 12% loss of production for every milliequivalent of chloride in the irrigation water (1 meq/L Cl = 35.5 ppm). The effects of chloride on avocado have also been studied under sand tank conditions, in which leaf necrosis symptoms are associated with elevated chloride levels in the plant leaf tissue and are accompanied by decreased ability of the leaves to carry out photosynthesis (Mickelbart et al 2007). The exact mechanisms by which chloride causes leaf burn symptoms are not completely understood, but appear to involve several factors. When sodium and chloride accumulate in the apoplast (the extracellular areas in the cell walls outside of the plant cell membranes), this causes dehydration effects that deprive the cells of water and result in cell death (Fenn et al. 1968; Munns and Tester 2008). At high concentrations, sodium and chloride also directly interfere with cell metabolism by competing with other essential ions that are components of enzymes (Munns and Tester 2008). Still other effects of chloride toxicity that are mediated by hormones such as ethylene which is induced as a stress response. These broad level effects have been particularly well studied in citrus in which the effects of chloride were shown to alter the expression of 869 genes in the plant leaf tissue following uptake of chloride salts (Brumos et al. 2009). It has also been suggested that water deficits cause changes in the nitrogen metabolism of plants, which leads to ammonia accumulation and contributes to the appearance of leaf burn symptoms (Lovatt et al. 1987).

While the first visible symptoms of chloride toxicity appear as leaf scorching, root growth is even more sensitive (Bernstein et al. 2004), and is affected well before symptoms appear in the foliage. The reduction in fine root growth leads to a decrease in the overall efficiency of the root system in accessing water and nutrients. Local water management districts have set 100 ppm of Cl as a target for maximum chloride levels for irrigation water. However, this value is controversial since the data on yield coefficients at different salinity and chloride levels are not yet available. In the study by Bernstein and coworkers, the threshold NaCl concentration that caused root and shoot growth reduction occurred between 5 and 15 mM. At a concentration of 15 mM NaCl leaf biomass production was decreased by 10%, whereas root length was reduced by 43%. This threshold concentration where root growth is affected is equivalent to approximately 200 ppm chloride, a level that is easily attained in saturated soils after 2 irrigation cycles without leaching, or after one irrigation cycle as the soil water dries to 50% of its available water holding capacity.

Salinity problems are more difficult to solve in clay soils

In conjunction with chloride, the physical properties of the soil can contribute to salinity problems. Sandy soils are relatively easy to leach, but have a low water holding capacity such that the soil must be watered more frequently to prevent water stress. At the other end, high clay soils that have poor drainage are particularly problematic in that salts are not easily leached, and irrigation water may be perched in the soil above hardpan layers where salts accumulate. Sodium is especially a problem in clay soils as it causes the soil aggregates to disperse, in effect sealing the soil so that it does not drain. In this case, gypsum applications can displace sodium with calcium and open the soil pores to allow better drainage. Studies with grape vines suggest that soil drainage and waterlogging following irrigation greatly affect salt uptake by plants (Stevens and Harvey, 1995). Under saline conditions, the use of chloride excluding grape rootstocks reduced leaf chloride concentration by 60% in vines with free-draining root zones but by only 18% in vines with waterlogged root zones. This suggests that there are interactions with soil salinity and the ability of roots to exclude chloride. Poor tree performance especially on heavy soils is further influenced by low oxygen and asphyxia (Schaffer, 2006). Altogether, it is clear that along with rootstock selection, irrigation management and determination of the proper leaching fraction are critical aspects of an integrated strategy for salinity and chloride management.

Soil water monitoring: the key to salinity management.

The first management consideration that growers must address is deciding when and how much to leach in order to avoid salt (and chloride) accumulation. This can only be accomplished by using water monitoring equipment to determine the soil moisture content at different depths and when salts have been sufficiently leached. By far, the worst possible practice is to apply water in frequent, short sets such that all of the salts remain in the upper profile and are never leached. On the other hand, long irrigation sets waste water and reduce profits, while also encouraging root rot.

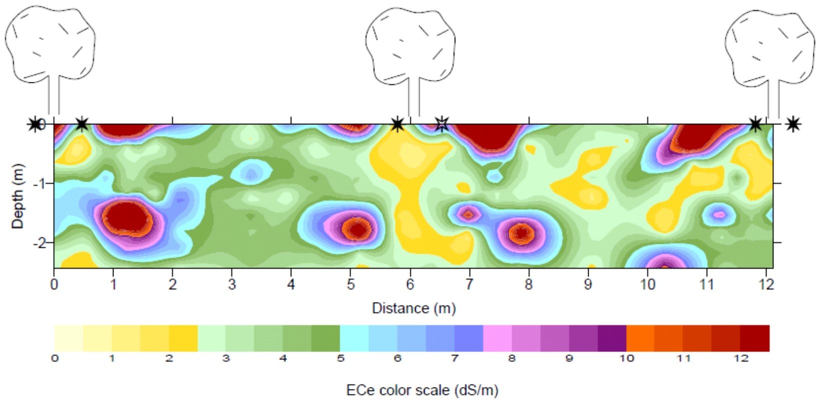
Irrigation uniformity is perhaps the greatest practical problem growers will encounter when trying to optimize irrigation practices to maintain low salt and chloride concentrations in the root zone. The general practice is to ensure that all trees receive adequate amounts of water such that some trees will be watered to excess in order to make sure that dry areas receive an adequate amount. This problem can be managed by ensuring that the flow is relatively similar for individual emitters and that pressure regulated emitters and flow valves are installed in the orchard. Water audits are offered for free or for a minimal charge by the local conservation programs, but can also be measured by using can collectors to measure total outflow and distribution patterns (Bender and Engle 1988). To effectively monitor soil water, the grower must use carefully standardized placement of tensiometers at different depths to monitor the likely distribution of salts and the efficacy of their soil leaching practices. In our experience, we set tensiometers in the middle of the wetted zone under the canopy, approximately 1 meter from the emitter.

The distribution of salts in orchard soils has been well studied to demonstrate variations in salt distribution in the soil profile both horizontally and at different depths (Burt and Isbell 2003). Here the main variables include the type of irrigation system and local variations in soil drainage. As shown in the Figure 4, drip irrigation results in a narrow column of low EC soil water around the emitter. However, in this case of shallow rooted trees like avocado, all of the fine feeder roots that take up water and nutrients are restricted to a depth of 10 cm in a small diameter zone under the emitter. Even with abundant root growth in this zone, a mature tree cannot obtain sufficient water to supply the canopy during hot dry weather..

In comparison, minisprinklers provide much better coverage of the soil zone under the tree canopy, but still leave edge effects depending on the uniformity of the spray pattern. Given the uneven distribution of water in soils with a microsprinkler system, deciding where to collect soil samples for measuring soil salinity is important. In our experience, values in leaf tissue chloride concentrations and soil salinity levels can vary for individual trees by more than 2-fold for neighboring trees along an orchard row, indicating that emitter placement and soil drainage patterns result in extreme variation. Normally, a grower will collect leaf samples from a composite of leaves across the orchard to monitor chloride uptake. This can disguise the variation that is actually occurring in the orchard as the average value for leaf chloride content across the orchard may be below the threshold of 0.25%, but half the trees still show leaf burn and are suffering from poor root growth. In part this variation along the row may be caused, in part, by interference of the spray pattern if the skirt of the tree canopy falls to the ground and blocks the distribution of water. It is important to insure that all obstacles preventing an even water distribution are removed. Checking the water distribution patterns of irrigation emitters on a regular basis can help greatly with salinity monitoring

To monitor water movement in the soil profile, our practice has been to use a Watermark data logger that records data from gypsum block tensiometers that are buried at different depths in the soil profile. Since most of the roots are located in the upper 10 cm, we place one gypsum block at this depth, another at 20 cm, and a third at 30 cm. When the soil is leached, the water flows past the lowest gypsum block and indicates that water has moved salts into the lower profile. The gypsum blocks are buried in the soil at a distance midway between the trunk and the edge of the canopy to capture data for the average area of wetted soil. With the recording equipment we use, gypsum blocks can be installed for three trees so that we can obtain an average across several trees in the zone. Ideally, the monitoring equipment is placed in different areas of the orchard that vary in slope, drainage, and soil texture.

Drip Irrigation



Minisprinkler Irrigation

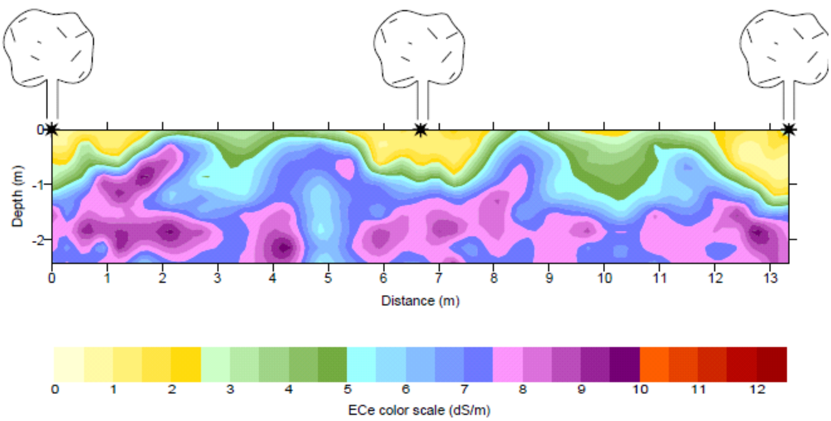


Figure 4. Salt accumulation patterns in the soil profile of orchard trees under drip (upper) and minisprinkler irrigation. Note that the majority of avocado tree roots are in the upper 10 cm of the soil profile. Under drip irrigation, most of the roots never receive water and those that are in the wetted zone are subjected to high EC such that the water is not available. Under minisprinkler irrigation, the roots are well wetted, but salts can vary along the row depending on distance to the emitter. At EC values greater than 4 dS/m, avocado can not take up the soil water. Figure and full article are available online at
http://www.itrc.org/reports/salinity/treecropsalinity.pdf

Rootstock Selection.

Over the past two decades, a large number of rootstocks have been evaluated for salinity tolerance. Early data has suggested that salt tolerance is greatest in West Indian rootstocks and poorest in the Mexican rootstocks (Embleton, et al. 1955; Ben-Ya'acov 1970; Gustafson et al. 1970). In southern California, West Indian rootstocks have not been used in breeding programs or as commercial rootstocks because of their putative poor cold tolerance. However, several West Indian varieties have been identified by Israeli researchers as having excellent salinity tolerance. In all of this previous work, one of the critical shortcomings has been the lack of information on the true heritage of the rootstock materials. New molecular methods that are being used to classify rootstocks will help to determine whether such a link between salt tolerance and race origin exists. In spite of this, we now know that within the Mexican race rootstocks used in California, there are differences in salinity tolerance (Oster and Arpaia 1992; Mickelbart and Arpaia 2002; and Mickelbart et al. 2007b). In these studies, two commonly used clonal rootstocks, Toro Canyon and Duke 7, have consistently demonstrated higher tolerance as compared to a third rootstock, Thomas. More recent studies indicate that DUSA is intermediate to Toro Canyon and Duke 7.

The physiological basis for salt tolerance has been studied in various model plant species, but not in avocado. As a general principle, high sodium is thought to displace calcium from the root cell walls, which causes leakage of potassium and other plant metabolites from the root (Picchioni et al. 1991). As reviewed by Kafkafi and Bernstein (1997), maintenance of adequate potassium concentrations and the proper potassium/sodium ratios in plant tissues is necessary for cellular function under saline conditions. Interestingly, in citrus chloride accumulation in the leaf tissue is also scion dependent when different scions are grown on the same rootstock (Garcia-Legaz et al. 1993). Once chloride is taken up and transported to the scion, the physiological affects of high chloride are manifested by reduced photosynthesis, and decreased stomatal conductance, transpiration, and decreased gas exchange (Garcia-Legaz et al. 1993).

In citrus, highly saline water has been shown to reduce potassium, calcium, and magnesium uptake and rootstocks that accumulate calcium appeared to have reduced salinity stress (Banuls et al. 1990;

Alva and Syvertsen 1991). In lime trees, resistance to salinity is associated with chloride exclusion and high selectivity of the roots for potassium as opposed to sodium (Storey and Walker 1987). Nutrient interactions that influence uptake of chloride by avocado are not yet understood. High nitrate levels in the soil have been shown to prevent the uptake of chloride, provided that nitrate is supplied continuously at a molar concentration equivalent to half that of chloride (Bar et al. 1997). Selectivity in the transport of Cl and Na to the scion is also affected by the rootstock (Banuls et al. 1990). Altogether, these studies suggest that fertilization and plant nutrient interactions may play an important role in salinity tolerance, along with other management practices (Lahav 1987).

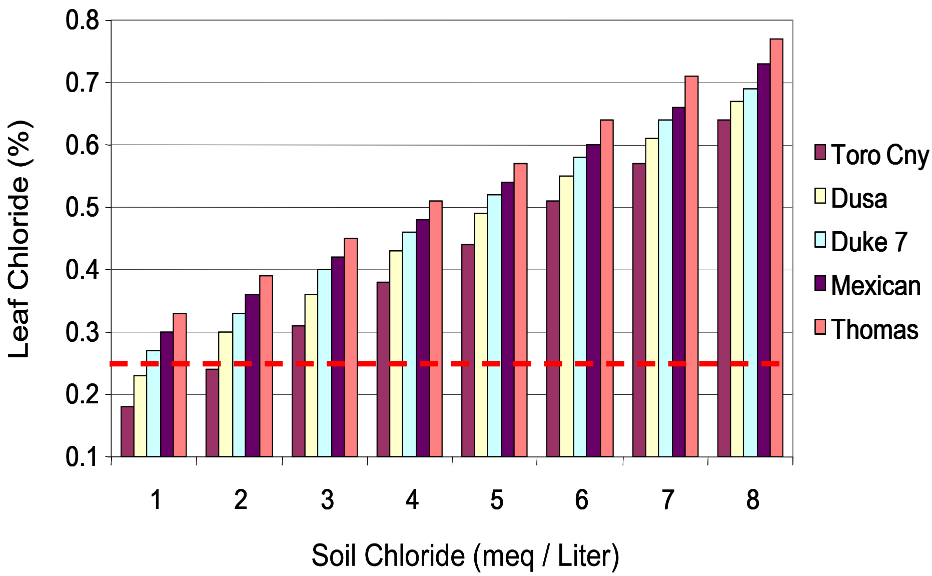


Figure 5. Predicted leaf chloride contents of Hass scions grafted on five rootstocks across a range of soil chloride concentrations. Predicted values are modeled from empirical data collected in 2008 and analyzed using an artificial neural network to separate out the effects of chloride from other variables. The predicted values here are based on fixed variables with soil ECe = 4.0 dS/m; water EC 0.8 dS/m; soil pH7; Clay 30%. The dashed bar indicates 0.25% leaf chloride content at which leaf burn symptoms appear.

Ongoing studies supported by the CAC are now examining the interactive effects of salinity and chloride across the range of soils where avocados are grown in California. Our current study includes

14 locations and 5 rootstocks, including clonal Toro Canyon, Thomas, Duke 7, DUSA (aka Merinsky 2), and non clonal Mexican rootstocks. All trees that were selected are within the age range from 3 to 6 years, and the sites are located in areas varying in irrigation water quality, climate, and soil texture. At each site, we have permanently tagged 15 trees per rootstock for leaf and soil analyses. As part of the setup for each site, we have installed WaterMark data loggers that allow us to keep track of the irrigation schedule and soil leaching events. Early results from these studies show that Toro Canyon and DUSA are the best rootstocks for excluding chloride, and that use of these rootstocks can reduce chloride uptake by as much as 2 fold in soils with low chloride and by 30% in soils with high chloride concentrations (Figure 5).

Breeding for salinity tolerance so far has relied on traditional approaches in which large numbers of seedlings are planted in highly saline soils and are then selected based on observations of their field performance when grafted to commercial cultivars. Another more technologically sophisticated approach with citrus has been to genetically engineer trees with a gene for salt tolerance that has been taken from yeast (Cervera et al. 2000). To date, the gene has been successfully transferred, but the trees have not yet been actually tested. One of the long term goals of earlier research has been to develop new avocado lines through traditional breeding blocks. Another approach that holds promise for evaluation of new materials is the use of microsatellite markers which can be used to draw linkage maps for important traits.

Future Directions

Along with rootstock selection, management of soil biology is perhaps one of the most exciting new directions that have strong potential application for improving salinity tolerance and drought in avocado. Recent studies have shown that certain plant growth promoting rhizobacteria (PGPR) can alleviate salinity stress and improve water use efficiency by removal of ethylene from the rhizosphere (see review:Yang et al. 2008). Ethylene is produced by the plant roots in response to drought and salinity stress and results in the cessation of root growth. When the root system fails to fully develop, water use and nutrient use efficiency decline and the tree may realize additional stress. Soil inoculation with PGPR breaks this cycle by removal of ethylene via an enzyme called aminocyclopropane deaminase (ACC) that destroys the precursor chemical that is otherwise converted to ethylene. Once root growth is restored, crops increase their root surface area and are better able to extract water and nutrients from the soil. This has not been tested for avocado, but merits exploration for increasing water use efficiency.

Summary

One of the most pressing questions today is how to best manage soil salinity while simultaneously optimizing water use efficiency. The management of salinity must consider both the effects of total dissolved salts and chloride concentrations in the irrigation water. Empirical data used to construct production function models show that total dissolved salts affect yield at EC_{iw} values above 0.6, with a rapid decrease in yields above this threshold concentration. Similarly, chloride affects root growth at very low concentrations that are easily attained following irrigation with water containing ~100 ppm chloride. Reductions in root growth will have concomitant effects on nutrient and water use efficiency along with yields. Management practices to reduce salinity and chloride are based on water monitoring to determine the volume and duration of water that must be applied in order to obtain effective leaching. General recommendations are to use a 10 – 20% leaching fraction at each irrigation to maintain average root zone salinity below EC_{sw} 2.0. However, local variation in irrigation emitter water distribution patterns and soil drainage along the row complicate efforts to monitor salinity. Current research is aimed at determining the yield reductions that can be anticipated at different chloride and salinity levels for the commercially used rootstocks in California. This research should help to determine the degree of benefit there may be in switching to salt tolerant root stocks when dealing with different water supplies and soil types. As water costs continue to increase and supplies dwindle, a thorough cost-benefit analysis is needed to optimize water use efficiency versus yields. New research on soil inoculants that reduce stress ethylene and enhance root growth may lead to methods for improving water use efficiency. All such practices require scientific proof that they are effective for improving avocado yields and tree performance on saline soils.

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