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# Managing Soils for Avocado Production and Root Health

***Abstract***

Management of avocado trees for optimal yields requires the maintenance of a healthy root system that is fully functional for nutrient and water uptake and growth of beneficial microorganisms that help to suppress root disease. Many different physical, chemical and biological factors influence root growth, all of which interact to influence conditions for development of the root system. This review provides an overview of best management techniques that growers should consider and examines the effects of individual soil factors on root function. The benefits of mulching, proper fertilizer timing, irrigation and salinity management are considered in detail as variables that can be managed to optimize avocado yields and root health.

## Introduction

The proper management of fertilizers and water and the control of root diseases are central concerns for avocado growers who often have soils that pose difficult challenges for crop production. While general recommendations can be made based on well established agronomic principles, the optimization of best management practices requires a careful consideration of the soil chemical and physical properties. Across the different areas where avocado trees are grown in southern California, soils vary from sands to decomposed granite and heavy clays, each of which requires different management techniques. This review examines the most important soil factors that affect tree nutrition and root health, with a particular emphasis on soil physical and chemical properties that affect root growth. Where practical, suggestions are provided for specific management practices related to mulching, irrigation, and fertilization on different soil types.

## Soil Physical and Chemical Properties

The first step in evaluating soils for avocado production is the determination of the soil physical and chemical properties. An ideal soil should be well drained, with good physical structure to facilitate root growth and provide adequate amounts of water and oxygen to the trees. To a large extent, both the physical and chemical properties of a soil are predetermined by the soil texture, which refers to the relative proportion of sand, silt, and clay or particle size classes (http://soils.usda.gov/technical/aids/investigations/texture/). Various methods can be used to determine soil texture with the simplest being a “feel” test that can be done by hand, or more precisely by a sedimentation test that involves mixing a known volume of soil with water and allowing it to settle while measuring the settled volume over time. Sands are relatively large and coarse and have no electrical charge and are thus inert particles that feel gritty to the touch and settle out quickly in the sedimentation test. Sands contribute mostly to development of intermediate size pore space for water drainage and aeration, but by themselves are very poor substrates for plant growth. Silt and clay fractions represent progressively smaller particle size classes, with silt being relatively inert and clays being the smallest particles that are formed by weathering of certain types of parent rock materials that develop a net negative electrical charge during the weathering process.

Among the different particle size fractions, clays are particularly important for determining soil physical structure and for providing the main source of cation exchange capacity that allows the retention of positively charged nutrient elements such as ammonium $NH4^{+}$, calcium $Ca^{++}$, magnesium $Mg^{+}$, potassium $K^{+}$ and sodium $Na^{+}$. The ability to hold these cations on the surface of the clay minerals is referred to as the cation exchange capacity (CEC), and is expressed as the milliequivalents of positive charge per kilogram of soil. This varies for different types of clays and the proportion of clay in the soil. Along with the mineral fraction of the soil, organic matter also contributes greatly to the physical and chemical properties of the soil, conferring additional cation exchange capacity, and contributes to the development of soil structure.

A loose friable soil is essential for allowing root growth extension as the root tips penetrate through the soil matrix. The idealized soil generally has about 50% pore space, which is essential for allowing the diffusion of gases into and out of the soil, for water infiltration, and for providing pore space through which the roots can grow into the soil. The large pore spaces in the soil are formed primarily by the process of soil aggregate formation which is driven by microbial incorporation of organic matter into the soil and binds the clay and silt particles into small peds that confer physical structure to the soil mass. Thus two of the most important physical properties that are used as indicators of soil quality and good soil management are specific properties referred to as bulk density and soil aggregate stability.

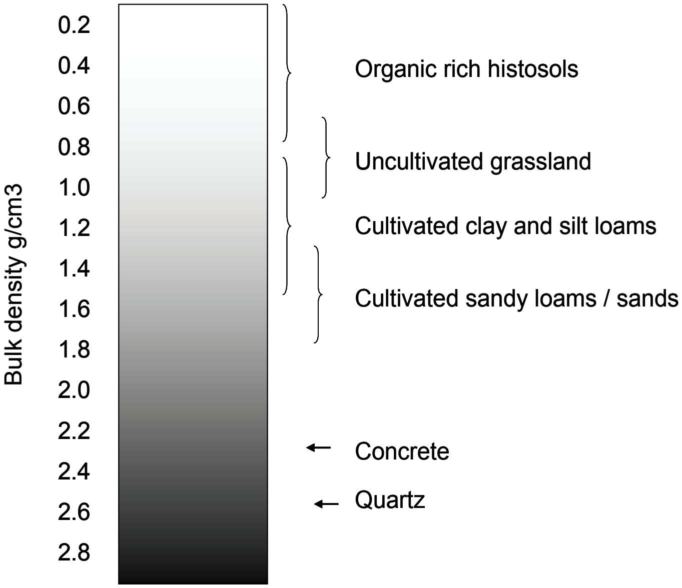
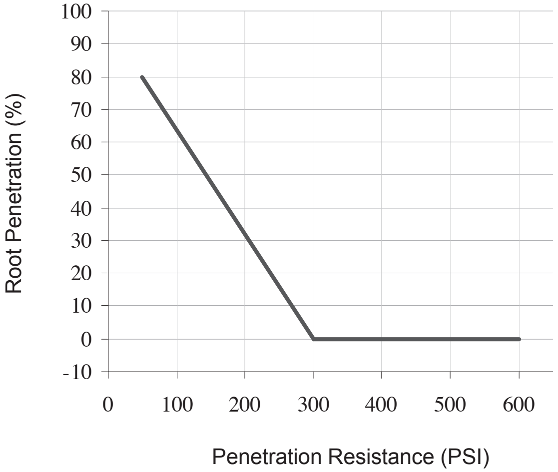


***Figure 1.*** *Typical bulk density values of soils having different soil textures. Organic matter promotes soil aggregate formation which results in formation of large pore spaces and lighter soil bulk densities. Sandy soils tend to have poor aggregate formation and have much higher bulk densities even than clay soils.*

Bulk density is simply a measure of the weight per unit volume of soil. Since the air space does not contribute to the soil weight, the bulk density value can be used to determine the actual pore space in the soil. A solid mass of soil particles has a typical weight of 2.65 grams per cubic centimeter. Hence, a bulk density value of 1.3 means that the soil has approximately 50% pore space. In addition to the total pore space, the pore size distribution, meaning that there are both large and small pore sizes, also comes into play for providing both large pores through which the roots can grow and small pores where water can be adsorbed and delivered to the roots through capillary flow. The formation of soils with good pore size distribution is facilitated by the formation of stable soil aggregates in which there are both large pores and channels for root growth and small pores within the aggregates that are cemented together by organic matter, fungal hyphae, and polysaccharides that are produced by microorganisms.

While seemingly complicated, the importance of soil structure and soil texture in controlling root growth can be measured directly. Bulk density directly influences root growth by limiting the pore space available for roots and by making the roots work harder to push their tips through the soil. In comparison to hydroponics, where there is no restriction for root growth, the root length and total number of roots declines in a linear fashion with incremental increases in bulk density. The maximum bulk density is attained at a value of 1.8 grams per cubic centimeter, at which point the soil is too compact to allow any root growth extension. Organic matter rich soils have the lowest bulk density and support the greatest root development (Figure 1). Cultivated clay and silt loams are heavier and have a bulk density between 0.8 to 1.4. The most heavy and difficult for plants are cultivated sandy soils that typically have a bulk density around 1.5.

Soil scientists can show a proportional relationship between root length and density of soils by growing plants in soils that have been compacted to different degrees (Figure 2). In this case, the bulk density is measured using a penetrometer, which is an instrument that measures the force necessary to push a steel point through the soil. A soil with low compaction requires a force of approximately 30 pounds per square inch to penetrate the soil. In compacted soils, the force required to penetrate through the soil can be as high as 300 lbs per square inch, at which point root growth ceases. Since the abundance of roots determines the ability of the plant to obtain water and nutrients, any factor that constrains root growth directly diminishes the potential growth of the tree and decreases both water use efficiency and plant nutrient uptake. As bulk density increases, both the water holding capacity and aeration also decrease. Thus the physical structure of the soil is one of the main components of soil quality.



Root growth decreases with increasing resistance until it ceases above 300 psi. Roots may still penetrate soil with natural cracks and pores are present. http://cropsoil.psu.edu/extension/facts/img/af63fig2.jpg

***Figure 2.*** *Relationship between soil penetration resistance and the relative percentage of root length development as compared to a hydroponically grown plant. Root growth is already constrained 20% simply by growth in non-compacted soil as compared to hydroponics. Even moderate compaction results in 50% or more decreased potential root growth.*

The interplay of soil texture with soil structure also determines the ability of trees to produce abundant root growth. This can be visualized using an artificially layered soil profile with horizons containing different types of soil. In the example shown in Figure 3, the development of corn roots is shown for a profile constructed with organic peat, clay and sand overlying a bottom layer of a loam soil. The plant roots are able to sense their local environment and develop well in the loose, nutrient rich areas of the profile but show limited growth or no growth in the heavier soils and sand. Although coarse sands are relatively well drained and provide intermediate size pores that promote drainage and gas exchange, sandy soils lack pore sizes that are needed for root extension so that roots may fail to penetrate through this type of medium. Heavy clays, on the other extreme, have an abundance of micropores that contribute to water storage but that do not contain macropores for root growth and may be poorly aerated, thereby limiting the growth of roots that need oxygen in order to develop.

***Figure 3**. Root growth through a soil profile that contains an organic rich layer over clay with an underlying sand layer. Abundant root development occurs in the organic profile and continues into a clay layer, after which root growth fails to penetrate through the sand lens due to the high bulk density and inadequate pore space.*

In this manner, loam soils and loose organic matter enriched soils that contain a mixture of soil particle size classes provide the best situation by providing an environment having good aeration, water retention, and pore size distribution for promoting root growth and water movement to the plant. Field studies conducted on avocado root growth in different soil types confirm these relationships and the effect of soil physical characteristics on root depth and distribution (Durand et al., 1987). In the study by Durand, 18 year old trees were completely excavated in blocks to examine root distribution in different soil types. Interestingly, a consensus of all studies to date is that the most important factor affecting rooting depth is the uniformity of the soil profile, as avocado roots do not readily penetrate from one soil texture and structure into another. In uniform soils, more than 80% of the roots are found in the top 1.5 meters (4.9 feet) and in soil with a bulk density less than 1.7 grams per cubic centimeter. The field observations also show that avocado tree roots do not penetrate through sand lenses and in soils with high bulk density, the roots are confined to the upper 20 cm of the soil horizon.

Regardless of the starting soil texture, the introduction and accumulation of soil organic matter is essential for the development of soil aggregates that lead to soil structure and to the development of pore spaces for water and gas entry, root growth, and prevention of wind and water erosion. The second most common measure of soil quality is thus the measurement of the number and size of stable soil aggregates. To assist farmers with soil quality assessment, the USDA provides information to farmers at a website that describes a soil quality test kit that can be constructed from simple materials, along with procedures for measuring soil properties such as aggregate size and stability. When used over time, this can be helpful in determining whether the soil physical properties are being improved or maintained properly through the grower's management practices. Another simple, but more indirect measure of the soil physical structure is the measure of hydraulic conductivity, which measures the rate of entry of water into the soil using a ring chamber that is pressed into the soil and then filled with water.

The baseline values for physical and chemical properties have been measured by soil scientists who have now produced detailed soil maps for the entire United States. These maps can be accessed on the internet at the USDA Soil Web Survey (http://websoilsurvey.nrcs.usda.gov/app/). The survey is user friendly and begins with a request for the physical street address. The map centers on the address that was entered and then can be relocated to the specific field area using a satellite photo of the field that is displayed for the viewer. Once a location is fixed, the soil data including pH, hydraulic conductivity, texture and other soil quality variables can be displayed in a table report along with supporting interpretative text.

## Soil Texture and Salinity-Irrigation Management

One of the most important applications of soil texture is the use of this information to guide irrigation and salinity management practices that will vary for soils with different textures and structural properties. Heavy soils are subject to poor drainage, waterlogging, and accumulation of salts, all of which can damage the tree roots and increase the severity of phytophthora root rot (Stolzy et al., 1967). Avocado tree roots have a constant demand for oxygen and can die within a few days of submergence (Hass, 1940). The ability to tolerate soil flooding appears to vary for different rootstocks (Valoras et al., 1964). As the soil pore space fills during irrigation, and the air content drops below roughly 17%, the rate of oxygen diffusion becomes limited and the soil oxygen levels are depleted to less than 1% as compared to the 21% concentration that occurs in the atmosphere. When oxygen levels in the soil pore space decline to less than 5%, the roots will die within a few days. The problem with wet soils is greatest in poorly drained soils that have a high bulk density or poor soil structure (Ferreyra et al., 2007). This may also occur in otherwise well drained, but shallow soils that overlay a hardpan or rock layer that prevents the water from draining. Recent work suggests that avocado rootstocks may vary greatly in their tolerance to oxygen depletion (Hofshi, unpublished data). However, breeding programs have not yet included this as a trait for selection, and commercial rootstock varieties appear to be generally susceptible to this problem.

In addition to causing problems with poor root growth and aeration, heavy, poorly drained soils with inadequate soil structure also are the most problematic for salinity management. High levels of chloride directly impair avocado root growth and the tree is unable to extract water from the soil solution when the EC rises above a saturated paste extract salinity value of 4 dS/m. At this point, the soil solution contains salt at a level that prevents the osmotic entry of water into the root cells, and the tree can experience water stress even in a water saturated soil. Sodium accumulation in the surface soil also leads to dispersion of the aggregates, eventually leading to loss of the soil structure. This results in an increase in bulk density, decrease in macropore space for root growth, decreased soil aeration, and increased problems with waterlogging. As the drainage problems become more evident, it becomes increasingly difficult to leach the salt from the upper profile, and the problem can spiral out of control, leading to development of sodium and chloride ion toxicities that cause leaf burn, as well as diminished root growth and function, and increased incidence of Phytophthora root rot (Wager, 1942; Zentmyer et al., 1947; Borst, 1972). For these reasons, it is especially critical to manage heavy soils to improve their physical structure and drainage to the maximum extent possible. Irrigation timing and frequency also become especially critical in these soils, which should be carefully monitored to insure proper leaching to remove the accumulated salts from the upper soil horizon. This can be accomplished using tensiometers and suction lysimeters at different depths in representative areas of the orchard. Another important consideration is the total wetted soil volume, as the roots will only proliferate in the areas containing adequate soil moisture (Cantuarias et al., 1995).

One of the most convenient methods for tracking water movement through the profile and insuring proper water amounts without over watering is to install a data logger with gypsum blocks at different depths in the soil. The soil water potential is a direct measure of water availability to the tree and takes into account the differences in water availability in soils of different textural classes. Sandy soils may be saturated at 10% water content and thus are easily depleted and require more frequent irrigation intervals. Clay soils, on the other hand, hold on to water so tightly that they may be "dry" but still contain 40% water by weight. The water potential measures water that is available to the plant irrespective of soil texture class, and thus can be used to guide when the soil should be irrigated. By installing watermarks or tensiometers at different depths, i.e., 6, 12, and 24 inches, it is possible to determine that adequate water has been provided to wet the soil to a 24-inch depth. The amount of water that was used to obtain this level can then be measured as a function of the time that was required and then used to calculate the time or volume of water that is needed to provide a leaching fraction for removal of salts. The volume of water that is required for leaching and the frequency at which the soil should be leached depend on the starting salinity of the irrigation water, natural leaching from rainfall, and soil characteristics. The overall efficacy of the leaching program can be determined by measuring soil water salinity with the suction lysimeters that sample water at different depths. This requires a capability for routine EC measurements which to date has dissuaded many growers who rely instead on testing laboratories and therefore do not closely monitor their soil salinities over time. Handheld salinity meters that are simple to use cost about $150 to $200 and provide instantaneous readouts that can be used to better optimize irrigation and salinity management. New soil probes that are soon to be introduced into the marketplace may also help growers to better manage soil salinity in problematic orchards.

Another important aspect of salinity management in heavy soils is the use of gypsum applications (Mace et al., 2001). Gypsum, which is the common name for calcium sulfate, provides divalent calcium, which has two effects that alleviate problems caused by salinity in heavy clay soils. The first effect is the displacement of sodium as calcium exchanges with sodium on the cation exchange complex. This causes the soil clay particles to flocculate into clumps and promotes soil aggregation and drainage. The sulfate ions then form ion pairs with sodium, which leaches out of the upper soil profile as sodium sulfate. Gypsum can be supplied either in a solid mineral form that is broadcast or can be micronized into small crystals that can be dispersed through the irrigation water using a fertilizer injector. Studies examining the effect of dispersion of soil and plugging of soil pores show that aggregate dispersion can occur even with irrigation water containing low sodium, especially following rainfall that leaches out divalent cations (Mace et al., 2001). Gypsum amendments also have direct antagonistic effects on Phytophthora and can help inhibit the development of root rot (Duvenhage et al., 1991; Messenger et al., 2000). For all of these reasons, gypsum applications are highly recommended for routine use in avocado production soils and are particularly important in soils with high clay content where promoting soil drainage and oxygen diffusion are essential for root health.

## Organic Matter and Mulching

One of the main management strategies for improving the soil physical and chemical properties, as well as for maintaining the activity of plant beneficial microorganisms, is the proper management of soil organic matter. Avocado is a subtropical tree that normally grows in a forest environment containing a layer of decomposing plant leaf litter that blankets the soil and that provides a source of slowly available nutrients while increasing the soil water content. In contrast to desert plants that have deep root systems to access water and nutrients, most of the avocado feeder roots that function for nutrient and water uptake are located in the top 12 inches (30 cm) of the soil, with many of the roots developing in only the top few inches under the mulch layer. In new orchards, one of the most important factors for success is to heavily mulch the trees to promote development of the organic matter layer in the surface horizon. The organic materials undergo decomposition and transformation into stable organic materials that include humic and fulvic acids, and the more stable humin (water insoluble) material that combines with clay and soil particles to form soil aggregates. Organic matter also acts like a sponge to absorb and retain water and provides cation exchange capacity for retention of nutrients. The mineral elements in the organic matter are also slowly released overtime to provide nitrogen, phosphorus, and potassium that are recycled and generate organic acids that dissolve trace metals and hold them in water soluble complexes that can be taken up by the roots. Lastly, cellulytic enzymes that are produced by microorganisms that decompose the mulch will attack Phytophthora, which contains cellulose in its cell walls.

Common organic materials that are used for mulching new orchards include composted yard waste and wood chips, which are now being recycled from green waste collection from residential areas. Other types of organic materials require more careful consideration in order to avoid problems. Animal manures and composted biosolids provide useful nutrient elements for fertilization but may also contain high amounts of salt that can damage the tree roots. These should be thoroughly leached, ideally prior to application to the orchard, or otherwise, soon thereafter, to push the salts down into the lower profile below the root zone. These materials will then continue to decompose and will release nitrogen, phosphorus, and potassium over time and are transformed into stable organic matter. A special concern is to inquire about the source of the organic material before it is introduced into the orchard, and if possible, the material should be inspected before it is trucked in and unloaded. Most green waste composters are careful with their source materials, but it is important not to introduce contaminated waste or diseased plant material into the orchard that has not been thoroughly composted to remove weeds and insect pests and plant pathogens.

With the recent increase in organically produced avocados, there has been considerable interest in organic amendments such as liquid compost and biologically enriched organic materials that are sold to promote root growth and as organic fertilizers. While these materials are rich in organic components, such as humic and fulvic acid and contain some levels of nutrient elements, they are generally very expensive in comparison to the use of traditional fertilizers and are often marketed based on testimonial observations of improved root growth and tree health. The controversy of biologically enriched materials for avocado production dates back to the 1950's in a classic paper by Martin (Martin et al., 1952). Little has changed since this first publication and to date, there is still no scientific evidence for most of these biological products that would suggest they are superior to other lower cost organic materials that are transformed in situ by soil microorganisms to the same end products that contribute to stable organic matter in the soil.

## Managing Plant Nutrients

Of the seventeen elements that are required for plant growth, the majority of these are supplied in abundant quantities in the soil and irrigation water. The nutrients required in the largest quantities, or so-called macronutrients, are nitrogen, phosphorus, and potassium. Avocado trees require inputs of macronutrient elements to replenish those that are removed by harvesting of fruit or that are not efficiently recycled within the soil. The calculation of fertilizer requirements has recently been facilitated by the availability of online calculators that can be used to obtain fertilizer recommendations. One such calculator is available in the tools section of avocadosource http://www.avocadosource.com/tools.htm. Another useful software program is AVOMAN, which is available at http://www2.dpi.qld.gov.au/avoman/ (Newett, 1999).

### Nitrogen

The most common limiting element for avocado production is nitrogen (Batchelor, 1933), which is used primarily for protein synthesis in the leaf and fruit tissues. The quantities vary depending on the tree compartment, with wood having very low nitrogen content, fruit containing 0.8% N (fresh weight), and leaves having a relatively high demand for nitrogen where it comprises 2-2.5% of the leaf dry weight. Much of the nitrogen in the leaves can be recycled during decomposition of the leaf litter that has fallen from the tree. Fruit harvest, on the other hand, results in removal of nitrogen that must be replenished with fertilizers or organic inputs. Avocado fruit contains a much higher protein content as compared to other fruit crops, with the fruit containing 0.7 to 0.8% nitrogen fresh weight, which is equivalent to approximately 1 gram of nitrogen per average size fruit (Lovatt, 1996).

Nitrogen use efficiency refers to the amount of nitrogen that gets into the tree versus that which is applied. Typical nitrogen use efficiency is 50%. The other 50% is lost by leaching of nitrate nitrogen and denitrification, in which microorganisms convert nitrate into $N_2$ and $N_2O$ gas during their respiration. In high pH soils, volatilization of ammonia is another pathway that can lead to nutrient loss. Using the N removal calculator at avocadosource.com, and assuming 100 kg (220 lbs) of fruit per tree with 100 trees per acre (~22,000 lb yield 10,000 kg), harvest of the fruit results in 61.7 lbs of nitrogen per acre. Given a 50% nitrogen use efficiency, 123 lbs of nitrogen per acre would be needed to provide for a large crop from a mature orchard. This is generally in line with the amounts of fertilizer that are used by avocado growers, which range from 80 to 160 lbs per acre (89-178 kg per hectare)(Lovatt, 1996). These quantities are of course adjusted for trees that are of different age and size or planting densities and in accordance with the expected crop yields. The nitrogen use efficiency will also depend on the form of nitrogen that is supplied, the soil nutrient holding capacity, and factors affecting N losses by leaching or denitrification. A major concern from the high levels of nitrogen is pollution of groundwater. Growers are also concerned with fertilizer timing to maximize nitrogen use efficiency, to improve fruit set, and to push fruit production versus promoting growth of the leaf canopy.

Specific recommendations for nitrogen fertilization have been derived from many studies over the past 75 years (Batchelor, 1933) and there are extensive papers on this topic (Embleton et al., 1972; Lahav et al., 1980; Meyer et al., 1992; Lovatt, 2001). Early recommendations by Gustafson (Gustafson, 1979) called for nitrogen to be provided in split applications in February and July starting with 1/8th pound per tree for two year old trees with incremental increases up to 1 ½ to 2 lbs per tree for 11 to 20 year old trees. More recent work has greatly refined fertilizer timing (Lovatt, 2001). In the review by Gustafson, fertilization was not recommended during the blossom and fruit setting period of March to June. In contrast, recent studies by Lovatt show that yield and fruit size could both be increased by applying N during early shoot development in the fall flush (mid-November) and again during early fruit set (mid-April). The precise timing is best matched to the actual phenological stages that vary depending on the climatic zone, with the first (fall) stage occurring when shoot apical buds have four or more secondary axis inflorescence meristems, and during the spring, when the trees are at anthesis to early fruit set and have initiated the vegetative shoot flush at the apex of indeterminate floral shoots.

Timing of fertilizers also must be considered in relation to soil chemical properties. Only the positively charged form of nitrogen, $NH_4$, can be held in soils on the cation exchange sites in clay and organic matter. This form of nitrogen is slowly converted to nitrate, $NO_3^-$ nitrogen, through the action of nitrifying bacteria that use the $NH_4^+$ ion as an energy source. The $NO_3^-$ ion is highly subject to leaching and further losses by denitrification. Leaching removes the nitrate ion below the root zone and results in nitrate pollution of ground water. Denitrification is facilitated by high microbial activity under low oxygen conditions where nitrate is used as an alternative electron acceptor for microbial respiration. Thus high soil moisture, high soil carbon levels, and high nitrate levels together promote the loss of nitrogen by this pathway. In some cases, half of the applied nitrogen can be lost by denitrification. High rainfall can also leach out nitrate nitrogen and is a major loss route leading to pollution of groundwater.

In addition to fertilizer nitrogen, this element is also provided to trees through nutrient cycling from decomposing plant litter, mulch, and can be provided entirely to the trees by additions of manure and other organic amendments. Typical levels of nitrogen in composted organic materials are 15 to 20:1 on a dry weight basis, or 5 to 7% N by weight. If the soil contains 2% organic matter, this represents 20,000 kg of organic matter per hectare (17,850 pounds per acre), containing ~1000 kg (892 lbs) of nitrogen, respectively. In this manner, organic matter decomposition from leaf litter and organic amendments can deliver large quantities of nitrogen to the crop. An advantage to this form of nitrogen is that organic nitrogen provides a slow release as the organic matter is mineralized to carbon dioxide and nutrients. In nature, this is the most efficient process for maintaining a closed nitrogen cycle in soils.

## Phosphorus

Avocado orchards in southern California are routinely fertilized with phosphorus fertilizers but seldom show responses to this fertilizer nutrient. In general phosphorus levels in most soils in this region are relatively high in comparison to the tree demand and crop removal rates. Avocado leaf tissues normally contain 0.1 to 0.15% P. In sand culture, P deficiency symptoms manifest as decreased vegetative growth, small leaves, early leaf drop, and branch dieback (Lahav et al., 1980). Phosphorus is primarily found in soils in the form of minerals, including iron and aluminum phosphates in acid soils, and calcium phosphates in neutral and alkaline pH soils. Dissolved phosphorus concentrations in solution are very low due to the low solubility of these minerals, with a maximum availability to plants at pH values between 6.5 and 7.0. Due to the low solubility of phosphorus, this element is often limiting to plants with coarse root systems. This is overcome by formation of symbioses with mycorrhizal fungi that form vast hyphal networks in the soil that function to transport phosphorus and other diffusion limited elements (Fe, Zn, Cu) to plants. Fertilizer forms of phosphorus include soluble salts such as ammonium phosphate and triple super phosphate. Other forms of phosphorus include organic materials and manures. In general, manures contain relatively high amounts of phosphorus and potassium as compared to nitrogen. Thus the use of manures to fertilize trees with nitrogen results in excessive application of phosphorus, leading to accumulation and storage of this element in the soil in mineral forms. All phosphorus containing materials, whether fertilizer phosphorus, phosphorus acid, and phosphorus liberated from organic materials undergo very rapid transformation to minerals that are precipitated out from the soil solution. This leads to large reserves of phosphorus that can supply this element for many years before depletion occurs.

Phosphorus is also supplied to avocado orchards indirectly by use of phosphorous acid containing chemicals that are used to treat avocado root rot, either by inclusion in the irrigation water or by trunk injection. Generally phosphorus fertilization will not be a concern except in acid sandy soils with low reserves such as in San Diego's Fallbrook sandy loams, Florida, and in coastal areas of Queensland and New South Wales in Australia.

## Potassium

Avocado trees have a relatively high requirement for potassium, but as with phosphorus seldom show a response to potassium fertilizers, indicating that there are abundant reserves of this element in most California soils. In contrast to phosphorus, potassium is relatively soluble and is easily leached from soils with a low cation exchange capacity. Orchards are routinely fertilized with potassium, but the importance of fertilization is greatest in sandy soils where this element is readily leached below the root zone. As with phosphorus, manures and other organic materials contain excess potassium in relation to nitrogen. Thus organically managed orchards that use manures and other organic materials to supply nitrogen will generally have abundant potassium.

## Micronutrients

Of the many different elements that are required in trace amounts for plant nutrition, only iron and zinc are of concern to avocado growers. Both iron and zinc are relatively abundant in soils where they occur as iron oxide and zinc oxide minerals, but nonetheless are often deficient and are difficult to correct. The solubility of these minerals is directly controlled by pH, with iron oxides and zinc oxides being most soluble under acid conditions. For every unit increase in pH, iron oxides and zinc oxides decrease in solubility by 1,000 fold and 100 fold respectively. At neutral to alkaline pH, these elements are essentially insoluble and must be provided to the tree in an organic complex or chelate. In this case, the organic molecule, generally an organic acid, or the chelate function by attacking the mineral surfaces to strip out the metal and form a complex that contains the metal ion within a shielded center that is enveloped by the organic molecule. The complex then moves by diffusion and mass flow to the plant roots where it is released into an ion channel and exchanged with another carrier, generally citrate, within the plant. The citrate metal complex then is transported through the xylem to the leaf tissue and incorporated into various molecules that use these metals for reactions involving energy transfer and electron transport.

In alkaline soils one of the main factors that contributes to iron and zinc deficiency besides the low solubility of these elements is interference from dissolved carbonates that form from dissolution of calcium carbonates (lime, seashells), and that are generated by respiration of the roots when $CO_2$ respired by the roots dissolves in the soil solution to form carbonic acid. Carbonates are also taken up by the plant and strongly interfere with the binding and transport of the metals by citric acid in the xylem; hence the difficulty in treating these trace-metal deficiencies. Often zinc and iron deficiencies show up in hotspots in the orchard in areas that contain free lime or calcium carbonates (Crowley et al., 1995). The symptoms will be most severe in heavy, poorly drained soils where $CO_2$ accumulates in the root zone (Crowley et al., 1995).

One of the most important considerations in treating trace-metal deficiency is correct diagnosis of the problem. Zinc deficiencies occur in both acid and alkaline soils. In acid soils, zinc deficiencies result when zinc has solubilized and leached into the subsoil so that total soil quantities are depleted in the root zone. Here an application of zinc sulfate will provide a quick and easy response. In contrast, both iron and zinc deficiency can occur singly or together in neutral and alkaline soils. In this case, visual diagnosis of the deficiency is not adequate as a deficiency of either metal is manifested by nearly identical symptoms that appear as interveinal chlorosis or yellowing of the leaf tissue between the leaf veins, and that show up primarily in the new foliage. Because there has been so much emphasis on zinc, avocado growers have often applied zinc fertilizers as part of their fertilization regime when the real problem is iron deficiency. As more and more zinc fertilizer has been applied over the years, the levels of zinc in many soils in southern California have reached near toxic concentrations. Thus it is essential to use plant leaf tissue analysis to determine which type of metal deficiency is actually occurring when deficiency symptoms arise and then treat with the appropriate material.

Zinc fertilizers have been applied to trees by foliar application, soil application of fertilizers, trunk injection and fertigation. Of these methods, trunk injection is the least effective, followed by foliar application, and either fertigation or soil application of fertilizers is the most effective (Crowley et al., 1996). Experiments examining foliar application of zinc using radioactive labeled zinc show that negligible quantities of this element are transported in the plant to other locations from the treated leaf surface. Among the different fertilizer materials, zinc and iron chelates applied to the soil or in the irrigation water are the most effective as compared to materials such as zinc sulfate. Alternatively, zinc sulfate can be applied along with acid forming materials such as sulfur to increase the metal solubility. In contrast to zinc where a variety of fertilizers are available, iron is applied only as a synthetic chelate. There are many different iron chelate formulations that have either EDTA or EDDHA as the active material. EDTA is unstable with iron at high pH and is a very temporary fix. The better but more expensive formulations will contain Fe-EDDHA. This chelate is very stable with iron at alkaline pH and will last for over a year, with the molecule acting as a taxi to shuttle iron continuously from iron minerals to the roots. Timing of any zinc or iron fertilizer should be matched with new root growth, as trees will not show any response until active new root growth occurs when the element is taken up by the new elongating roots.

## Managing Soils for Root Health

While the emphasis of this article has been on the relationship between soils and their ability to support root growth and nutrition, the chemical and physical properties of soils also directly impact the growth and activity of soil microorganisms that function for nutrient cycles in soils and that promote root growth by disease suppression and production of plant hormones. The activity of microorganisms is also important for formation of aggregates and has a positive feedback in creating a soil environment that is favorable for plant growth by promoting good soil structure, aeration, drainage, and root elongation. Among the different variables that are used to assess soil quality, soil biological variables are still the least understood and most difficult to interpret. This is due to the tremendous species diversity and complexity of soil microbial communities. Typical soils contain 25,000 to 50,000 different species of bacteria per gram of soil, and the species composition of the soil microbial community varies for different soil types and over time. The highly dynamic composition of microbial communities in soils makes it very difficult to determine what constitutes a “normal” community, and the large number of species that are present makes it very difficult and expensive to determine the community composition in a particular sample.

Most measures of soil biological quality rely on measurements of soil respiration and biomass. While all plant life is dependent on soil microorganisms, our inability to assess exactly how different management practices affect plant beneficial microbial activity makes it difficult to give specific recommendations. As a general rule of thumb, conditions that support high biological diversity and total microbial biomass tend to be associated with good soil structure and root health. Unfortunately, our lack of soil biological quality indicators limits the ability of soil microbiologists to scientifically determine the value of a wide range of microbial products that have appeared on the market. Most of these products are marketed based on testimonial statements, and there is little or no scientific evidence for the claimed effects. This does not mean that some such products do not have value, but can in some instances, lead to extravagant claims that do not have a scientific basis and that are probably too good to be true. For example, some companies market their products based on counts of bacteria in the material they are selling, and in some cases will enumerate specific species or types of bacteria that were added to the mix. However, when compared to the numbers of bacteria in soil, which typically range between 100 million to 1 billion cells per gram of soil, the net addition of bacteria is meaningless. Furthermore, soil inoculants may contain bacteria that have been cultivated under rich conditions in the organic medium, but that will quickly starve and die when they are added to soils. Studies on the fate of soil inoculants that are used for biocontrol of root disease or for bioremediation of soil contaminants generally show that greater than 90% of the inoculated bacteria disappear within a week, and the numbers continue to decline until they eventually vanish below detection limits.

Despite the uncertainty regarding many microbial products, there is great interest in developing scientifically based approaches for monitoring and promoting the populations of bacterial and fungal species that have been shown in carefully conducted laboratory studies to promote root growth and suppress plant pathogens. The majority of plant beneficial microorganisms that have been identified to date are those that can be readily cultured in the laboratory and include various species of *Pseudomonas*, *Bacillus*, *Streptomyces*, *Azotobacter*, and other genera. However, as less than 95% of the bacterial species in soil can be cultured in the laboratory, it is likely that these species represent a very small percentage of the total number of bacteria that interact with plant roots and root pathogens. Studies in which these bacteria are inoculated into soils show that very high population densities are required to exert significant effects that can be measured. For example, disease suppressive strains of plant growth promoting pseudomonads must be maintained at greater than 100,000 cells per gram of soil. One time inoculation of soils with these organisms fails to achieve these levels. On the other hand, experiments with citrus using a field based fermenter, in which bacteria could be automatically cultured and injected into the irrigation water at regular intervals, showed that phytophthora root rot could be suppressed by maintaining high densities of the suppressive bacterium. It is clear that more work needs to be done in this area to take advantage of manipulating microbial communities to enhance root growth.

## Future Outlook

Good soil management practices provide the foundation for sustainable agriculture and are essential for optimizing the productivity and root health of any agronomic or horticultural crop. In comparison to many crops, avocado trees, with most of their feeder roots proliferating in the top six inches of the soil profile, are especially sensitive to soil management practices. They are susceptible to damage due to poor aeration, waterlogging, salinity, and root disease. Avocado growers, on the other hand, take pride in a "hand grown" crop and are attentive to using the best methods available for producing high crop yields of quality fruit. This requires that individual growers be aware of the specific properties of their orchard soils and the best way to tailor their irrigation and fertilization practices. Research funded by the California Avocado Commission has provided the framework for development of best management practices, but requires a continual education program to make sure that recommendations are disseminated and followed by growers and grove managers. Management of soil physical and chemical properties can be achieved by proper use of organic amendments and mulches, routine applications of gypsum, and proper irrigation methods to avoid deterioration of soil structure through soil salinization. With the increasing cost of water and likelihood that growers will need to increase their reliance on saline groundwater or reclaimed water, there is still considerable room for improvement in water monitoring and salinity management practices. Likewise, fertilizer timing and best management of fertilizers for optimal production while avoiding excessive use of nitrogen and micronutrient fertilizers that can cause pollution need further study. Organic farming methods that are increasingly being used by growers will almost certainly be beneficial for promoting good soil properties but should be carried out scientifically to determine those practices and products that are beneficial and cost effective.

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