Review

Managing High pH, Calcareous, Saline, and Sodic Soils of the Western Pecan-growing Region

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Summary. Pecan [*Carya illinoinensis* (Wangenh. K. Koch)] soils in the arid western United States are characteristically high in pH, calcareous, and often saline or sodic. Economic production, when trees are grown in such soils, requires that growers pay particular attention to managing soil chemistry to avoid nutrient deficiencies, toxicities, or water deficits due to soil structural deterioration. Soil-applied acidulents, calcium-containing compounds, and water management are used by growers to manage high pH problems, sodic soil conditions, and salinity.

Depending on species, optimal growth and production of most tree fruit and nut crops occurs when soil pH is 5.5 to 7,0, as measured in a saturated soil paste, Within this pH range, exchangeable metals such

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Table 1. ***Elemental S (95%) needed 10 increase acidity of a 0.15-m layer of carbonate-free soil***[z]

Desired pH change	Sulfur (kg·ha^{-1}) Sand	Loam	Clav
8.5-6.5	2287	2857	3426
8.0-6.5	1368	1707	2288
7.5-6.5	569	919	1149
7.0-6.5	109	164	339

[z]*Adapted from California Fertilizer Association (1990)*

as aluminum and manganese are not toxic, whereas essential nutrients are available insufficient quantities for normal physiological growth to proceed with unimpaired soil structure (California Fertilizer Association, 1990; Gregory, 1988; Peacock, 1989; Stromberg, 1980), Soils having pH values as high as 8.0 also are considered productive and are commonly planted. Once pH values rise above 7 however, additional management is required, as micronutrients, most notably zinc and iron, become increasingly unavailable. Their volubility in the soil solution can decrease as pH rises; zinc volubility is highly pH-dependent; it decreases 100-fold with each unit increase in pH (Tisdale et al., 1985). In such alkaline soils, soil pH either must be reduced, or these nutrients must be soil-applied inexpensive chelated forms or sprayed on the foliage to maintain their sufficiency in the tree.

A large portion of the cultivated pecan acreage lies in the western United States, from western Texas to the interior valleys of California.

Soils typical of this region are alluvial, usually calcareous, sometimes saline, and slightly to considerably alkaline in reaction or even sodic, often having a pH >8; pecans prefer soils in the pH range of 6.5 to 7.0 (Sparks, 1977), In the western region, soil pH and presence of free lime results in the potential for acute deficiencies of micronutrients, including zinc and iron. Saline and sodic conditions often occur and require special consideration Growers must pay considerable attention to soil management to produce economic yields of pecans under high pH and calcareous, saline, and sodic soils. This paper discusses soil management and the use of soil-applied acidulents to offset high soil pH and calcareous conditions in the arid western region. Amending sodic and saline soils is reviewed,

Soil pH management

Maintaining soil pH within the range optimal for pecan tree growth and production is a major management goal of pecan growers, When growing pecans in alkaline soils, acidifying soil amendments maybe desirable to reduce soil pH. Several sulfur-containing products are the most common and cost-effective acidulents for reducing soil pH (Stromberg, 1980).

Elemental sulfur. Elemental sulfur, usually >95% pure, is the most common acidifying amendment used by pecan growers to reduce soil pH. Once applied and incorporated, the sulfur is oxidized to sulfuric acid, and its subsequent ionization releases hydrogen ions to reduce PH. Table 1 presents the approximate amounts of 95% sulfur required for varying degrees of pH change in several soil types under noncalcareous conditions. Pecan growers must consider several limitations of elemental sulfur that can reduce its effectiveness. Particle size is the most important characteristic effecting its oxidation rate; finely ground sulfur thoroughly mixed with the soil exposes the most surface area to oxidizing bacterial action (Stromberg, 1980; Tisdale et al., 1985). Under optimal temperature and moisture conditions, finely ground sulfur [(100%) <0.125 mm] can be converted to sulfuric acid within 1 or 2 months, whereas coarsely ground sources may take several years A range in sizes (e.g., 400% < 0.25 mm, 30% >0.25 mm, and 30% > 1.0 mm) provides for multiple-year oxidation and acidification.

Although particle size greatly affects its oxidation rate, elemental sulfur is generally slow to react because it requires a temperature-dependent bacteria, *Thiobacillus* spp. (*T. thiooxidans* is the most common), for oxidation to sulfuric acid (Tisdale et al., 1985). The bacterial oxidation requires warm soil temperatures It is slow at soil temperatures <21C and most rapid at soil temperatures ≥ 29C; conversion to sulfuric acid essentially stops when soil temperatures reach 10C (Stromberg, 1980). Growers apply sulfur in summer when soil temperature is warm for the most rapid effect,

Sulfur-oxidizing bacteria require oxygen to sustain their activity, Soil moisture approaching field capacity is optimal; waterlogged soils reduce bacterial action (Stromberg, 1980; Tisdale et al., 1985),

Sulfuric acid. Southwestern pecan growers also are looking at sulfuric acid for rapid soil pH reduction unestablished orchards. Sulfuric acid may bean economic option in only certain parts of the United States or the world, where it is a by-product of other manufacturing, It is injected in the fall only at the drip line of the tree at rates of 568 to 4000 kg of 95% acid/ha [at a tree spacing of 9.1 × 9.1 m(120 trees/ha), rates equal 4.7 to 33.3 kg/tree] depending on the amount of localized pH change desired. A relatively small area is treated, about two strips (one on each side of the tree) of about 3 × 9 m each, per tree. Thus, on a unit area basis, an extremely heavy rate of acid is applied. When fall injections are used, no phytotoxic effects on subsequent tree growth and production resulting from root damage have been observed.

Sulfuric acid may be more expensive than other sulfur amendments (Table 2), but it has the advantage of immediate pH reduction; direct application of sulfuric acid circumvents the need for any bacterial oxidation of elemental sulfur, When injected into a high-pH soil, the subsequent and immediate release of hydrogen ions, as sulfuric acid ionizes, creates a highly acidic zone that quickly increases micronutrient solubility. Irrigation following application increases the zone of pH change only slightly.

Sulfuric acid requires specialized equipment for application. Reliable equipment is now relatively common, and sulfuric acid injection is being used more frequently to amend high-pH soil, especially where local sources of the acid exist (e.g., as a by-product of oil-refining or copper-mining operations such as exist in the southwestern region).

Lime-sulfur. Lime-sulfur is a liquid that growers can inject into the irrigation water; it includes calcium polysulfide and calcium thiosulfate. Once in the water, finely divided sulfur compounds (partially oxidized sulfides, sulfites, and thiosulfate) are released, and, when incorporated into the soil, they require an oxidation reaction similar to elemental sulfur. The advantage of lime–sulfur is that its sulfur is very finely divided, which enhances the speed of oxidation and subsequent acidification.

Lime-sulfur is purchased based on its sulfur content, usually 24% It also contains 6% to 8% calcium, but this amount is so low that it is of doubtful value considering the much larger quantities present in the soil.

Other acidifying agents. Continued use of ammonium and ammonium-forming fertilizers like urea eventually will acidify soil (Tisdale et al., 1985). The process requires many years to achieve significant results, and the effect is confined only to surface layers or zones where applications are made. Reliance on these materials to reduce soil pH significantly in problem situations is not recommended.

Other acidifying sulfur-containing materials like urea-sulfuric acid (N-phuric) have been used in high-pH soils. It is doubtful that these materials would provide cost-effective, major pH correction, especially where free lime exists. The value of adding nitrogen and acid along with application costs must be evaluated against other alternatives.

Purchasing sulfur amendments, Sulfur amendments are added (and often purchased) based on their sulfur content. Table 2 presents the amounts of two sulfur amendments required to be equivalent to 100 kg of elemental sulfur.

Reducing pH in calcareous soils. Free lime generally is associated with high-pH soils. Pecan trees, like other fruit and nut trees, often exhibit micronutrient deficiencies, especially iron defi-

Table 2. ***Relative amounts of sulfur amendments used to acidify soils.***

Amendment	Amendment equivalent to 100 kg of elemental sulfur
Elemental sulfur (100%)	100
Sulfuric acid (95%)	320
Lime-sulfur (22% sulfur)	
32° Baume	365

ciency when grown in soils containing excessive free lime, i.e., calcareous soils; iron deficiency in calcareous soils commonly is referred to as lime-induced chlorosis.

Sulfur often is suggested as an amendment to counteract the lime and reduce pH. Free lime is a strong buffer against acidification of alkaline soils. When applied to calcareous soils, sulfur undergoes a second reaction, that of the sulfuric acid reacting with the free lime to produce gypsum ($CaSO4{\cdot}2H_2O$), carbon dioxide, and water The existence of free H ions is minimal until all the lime has been neutralized, Consequently, considerably more sulfur is required to reduce soil pH when lime is present. For example, it is generally accepted that 1 kg of sulfur is required to neutralize 3 kg of free lime (Tisdale, 1985), If a candidate soil contained 30g·kg^{-1}(3%) lime, neutralizing the lime throughout the soil profile would be cost-prohibitive.

Fruit and nut growers, including some pecan growers in the southwestern region, have used concentrated applications of sulfur or sulfuric acid to deal with high pH and free lime in the soil. The acidulent is placed in a concentrated band or injected to create a strongly acidified zone within the soil profile to increase volubility of the micronutrients, including iron, zinc, and manganese. In this manner, enough of the acidifying agent can be placed in localized areas to neutralize the strong buffering effect of lime. As micronutrients are required only in small amounts, such localized zones of acid soil often have been satisfactory for correcting micronutrient deficiencies. In the case of sulfur, several annual concentrated applications; i.e., localized applications of 9.1 to 22.7 kg/ tree, may be required to overcome excessive amounts of lime in the soil proximal to the tree, Due to the high costs of such amendments, only localized applications are needed to change micronutrient availability while remaining economic. It is doubtful that enough sulfur or sulfuric acid could be broadcast and incorporated uniformly to offset lime effects economically,

Correcting saline soils

High-pH pecan soils are often saline as well. A soil having an electrical conductivity (EC_e) of 0.15 to 0.20 S·m^{-1}(1.5 to 2.0 mmho/cm), as determined from a saturation soil extract, has enough soluble salt to interfere with tree growth and reduce production of most horticultural tree crops (California Fertilizer Association, 1990; Maas, 1986), Specific ions of these soluble salts, $Na^+$and Cl^- being most notable, accumulate in vegetative growth and cause increasing crop loss depending on their concentrations. Salt concentrations in the soil solution that approach 0.4 S·m^{-1}(4 mmho/cm) further affect growth through their osmotic effect of reducing water uptake.

Correction of a saline soil requires a grower to remove the salts by applying enough nonsaline irrigation to leach them below the root zone; correction is only possible when subsurface drainage is unimpaired, About 30 cm of nonsaline water is required to leach 80% of the soluble salts from 30 cm of soil; an additional 30cm may be required to remove 90% of the salts (Peacock, 1989). If water used for leaching also contains excessive soluble salts or if internal drainage within the soil profile exists, the potential for salinity correction will be considerably limited,

Salts are leached best with nonsaline water before planting a sensitive crop such as pecan; pecans commonly show leaf scorch from ions of excessive salts when the EC, of the soil saturation extract exceeds 0.2 S·m^{-1}(2.0 mmho/cm) (Miyamoto et al., 1986). Evaluating the relative sodium concentration using calcium, magnesium, and sodium concentrations in the saturated-paste extract to calculate the sodium absorption ratio (SAR) is helpful during the reclamation process, as the need for gypsum can be determined using these values,

Tree growth and production continue to deteriorate as EC, rises, and growth stops at EC_e4. (Miyamoto et al., 1986). Most salinity problems, however, are observed in established pecan orchards once irrigation begins; the source of irrigation water contains salts that, when applied to the land, accumulate in the soil, resulting in saline conditions.

Special water management is required to establish pecan trees grown where saline conditions are severe enough to limit economic production. The salt content of the soil is dynamic; as saline water is applied, salts are added, When the soil water is depleted as trees transpire, the salt content of the remaining soil water increases, resulting in increased salt stress (Maas, 1986), Salinity hazard can be minimized by irrigating frequently and applying with each irrigation slightly more water than the crop requires, Such an in-season irrigation strategy, over time, reduces the soil's total salt content by leaching excessive salts, keeps the soil solution dilute of salts and, ensures water extraction from the largest portion of the root zone possible; infrequent irrigation, allowing the soil to dry down in the interim, forces trees to extract water from areas of the profile with highly concentrated salt, Further leaching can be accomplished by applying a full irrigation once or twice during the winter, Unless adequate leaching is carried out, soil EC_e usually approaches 1.5 or more times the EC_w of the irrigation water,

It must be emphasized here that only leaching corrects salinity; soil amendments, such as sulfur or gypsum, are not effective unless their addition improves water penetration, which subsequently improves leaching, or where gypsum reduces the relative sodium concentration.

GLOSSARY

Alkaline soil. **Any soil having a pH >7.0, as measured in a saturated paste.**

Saline soil. A soil **containing enough soluble salts to result in an electrical conductivity (EC_e) of the saturation soil extract of 0.4 S·m^{-1}(4 mmho/cm) or greater, with the exchangeable sodium <50 g·kg^{-1}(15%). The pH of the saturated soil paste is usually <8.5. Fruit and nut tree growth and production often are affected adversely when the soluble salt content of the soil results in an EC_eas low as 0.15 to 0.2 Sm^{-1}(1.5 to 2.0 mmho/cm). The principal cations in a saline soil are calcium, magnesium, and sodium. The main anions are chloride and sulfate. Sodium and chloride are usually the specific ions causing reduced tree growth and production. The term white alkali often is used in reference to saline soils as the soluble salts accumulate at the soil surface when water evaporates. Saline soils are often well flocculated and permit good water penetration, indicating the predominance of calcium and magnesium ions.**

Sodic soil (also referred to as an alkali soil). A **soil having exchangeable sodium of >150g·kg^{-1}(15%) of its total cation exchange capacity and an electrical conductivity of a saturation extract of <0.4S·m^{-1}(4mmho·cm^{-1}). The pH of a sodic soil is usually >8.5. Sodic soils lose their granular structure and become puddled, precluding water penetration. The vernacular black alkali is sometimes used in reference to a sodic soil because dispersed organic matter on the soil surface results in a slick spot that is nearly impervious to water. In most cases, crop damage results from poor physical condition that limits water movement into the soil. Fruit and nut trees, however, also can be affected adversely by the exchangeable sodium before the exchangeable sodium percentage (ESP) is sufficient to deteriorate soil structure, often when the ESP reaches 10 or more.**

Saline-sodic soil. **Saline-sodic soils have an electrical conductivity of >0.4S·m^{-1}(4 mmho/cm) and an exchangeable sodium percentage of >150g·kg^{-1}(15%). Their physical properties are similar to saline soils until they are leached of their soluble salts. Then these soils take on characteristics of a sodic soil.**

Calcareous soil. **Any soil containing free lime (e.g., calcium carbonate or calcium magnesium carbonate). Very common in the southwestern region. Most saline soils are calcareous.**

Correcting sodic soils

Sodic soils occur in the western pecan-growing district. A sodic soil contains an excessive amount of sodium on its cation-exchange complex. Although a sodic soil is defined as one that has an exchangeable sodium percentage (ESP) of >.15 Sm^{-1} (15%), detrimental effects occur to most horticultural crops at levels of 0.10 Sm^{-1} (10%) or below; sodium at these levels adversely effects the soil's structure by causing it to lose its granular structure, becoming impervious to air and water. Nearly all sodic soils in the southwestern and western regions are saline as well and have a high pH. Leaching to remove the soluble salts of a saline soil first requires attention to the sodic conditions that impair water penetration,

To correct a sodic soil, it is necessary to replace the excessive sodium on the cation-exchange complex with calcium. Growers often correct a sodic soil by working in calcium via the soluble salt gypsum ($CaSO_4{\cdot}2H_2O$). The divalent cation calcium readily replaces the sodium, which then forms sodium sulfate to be leached from the profile. Calcium ions can be added indirectly, if the soil contains large amounts of calcium, by applying an acidulent, such as sulfur, lime–sulfur, or sulfuric acid, which reacts with the free lime to form gypsum. The calcium content of the soil and the amount of soil amendment required for sodic soil reclamation can be determined by a reliable soils laboratory, The analysis often is referred to as a gypsum requirement, and is reported as the amount of gypsum required to reclaim a specified amount of soil,

Economic pecan culture in the arid western growing region requires considerable attention to soil and soil chemistry management for optimal growth and production, High pH, salinity and sodic and calcareous soils are common and must be managed properly through proper diagnosis, management, or amendment to avoid the nutrient deficiencies, toxicities, and water availability typical of these conditions. Properly managed, pecan soils of the arid western region can be some of the most productive in the United States when managed correctly.

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