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Salinity Management of Walnut

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High yields and walnut quality are best achieved with soils and irrigation water that have desirable levels of salinity and the correct composition of salts. Field problems often associated with salinity include decreased soil-water availability, reduced rates of water infiltration into soils, and accumulation of specific elements to toxic levels in plant tissue.

In this chapter we advocate the use of soil and water analyses as practical and economical management tools. We will discuss how to collect representative soil and water samples, understand terms used in an analytical report, check the quality of an analytical report, diagnose different types of salinity problems, and make remedial management decisions. Most important, this chapter will emphasize that achieving successful, long-term salinity management requires sound irrigation management.

SAMPLING

One of two philosophies can be applied when sampling soils and water to diagnose and manage salinity problems. Sampling can be conducted (1) annually or biannually for routine monitoring or (2) only when necessary to troubleshoot problems. We advise routine sampling to diagnose salinity conditions during early stages of development, when remediation is more easily achieved with less expense and fewer adverse effects on the orchard.

Irrespective of sampling philosophy, representative soil and water sampling must be achieved for analysis results to be of value. Results from unrepresentative sampling may be misleading and costly. Although obtaining representative samples involves some effort and expense, analyzing salinity of an 80-acre orchard should not require more than 8 hours of labor and $480 ($6/acre/year) annually.

Soil Sampling

Obtaining representative soil samples is challenging because salinity varies considerably throughout the orchard. Perhaps the most important step is to composite samples of soil. Begin by sampling the same depth of soil in at least nine locations within a parcel of land considered to have similar soil types. Mix the samples together to form one large sample. Air-dry 1 pound of it and submit it to a laboratory for salinity analysis. Repeat the compositing and drying for each soil depth of interest. Compositing minimizes the number of soil samples requiring analysis, while achieving the most representative sampling.

Soil samples should be collected at the same time each year with respect to rainfall patterns and irrigation practices. This ensures that salinity distribution and accumulation are not influenced by significantly different levels of applied irrigation water and evapotranspiration. We suggest sampling after harvest to provide a salinity assessment in an orchard when root zone salinity is highest. (Irrigation is commonly delayed during harvest, so salinity accumulates in the root zone.) Also, fall sampling gives the most advanced notice that additional irrigation water may be needed for salinity control during the winter season, when the trees are dormant and least sensitive to overirrigation.

The method of irrigation and the ability to apply water uniformly must be considered to collect representative samples. In flood-irrigated walnut, sampling 5 to 10 feet to the side of a tree row will be representative. In sprinkler-irrigated walnut, in contrast, sample across the sprinkler pattern to ensure that the composite includes soils from the center of the wetting pattern (these receive the most applied water) and soils from the edges of the wetting pattern, where salinity tends to accumulate.

Variable soil textures contribute to nonuniform salinity levels in an orchard. Sandy loams tend to have lower salinity than silt loams and clay loam because infiltration rates are often higher and leaching is greater in sandy loams. Sampling from similar soil types reduces variability in salinity levels. Uniform tree growth is a good indicator of uniform soil type.

Take soil samples from several depths because each depth reveals different information. A sample from 0 to 3 inches from the surface can reveal crusting problems. Surface soils containing salinity and sodium levels far in excess of levels in the irrigation water strongly indicate that soil crusting restricts water infiltration and that irrigation water quality may present a problem. Sampling subsoils in 12-inch increments to 48 or 60 inches will show the typical depth of water penetration from irrigation by indicating zones of salt accumulation. The salinity levels for the 12-inch increments can be averaged to determine the average root zone salinity, which is what trees respond to in terms of osmotic effects on available soil-water and specific ion toxicities.

Water Sampling

Sampling irrigation water for salinity assessment is much simpler than sampling soils. First rinse a plastic container in the water supply that is to be sampled. Collect a small sample (4 to 8 oz) by completely filling the container with water. This eliminates air, which would otherwise promote calcium carbonate ($CaCO_3$) precipitation.

Before taking a sample from a well, let the pump run for at least 30 minutes. This should be sufficient time to flush the well of static water and establish the water elevation that represents the primary water-bearing strata. Wells in stable aquifers may not require annual sampling, but wells in declining aquifers require frequent sampling. If groundwater depths are declining, collect a representative water sample for laboratory analysis to establish a baseline. Then invest in an inexpensive portable electrical conductivity meter, which will cost from $25 to $50, and monitor the total salinity of the well water. Submit a new sample for analysis when the total salinity increases 20 percent.

To establish a baseline for surface water, take samples from canals or ditches with flowing water. As described for groundwater monitoring, use a portable electrical conductivity meter to determine how often the surface water supply should be analyzed.

If possible, submit a water sample for analysis on the same day that it is collected. If the sample must be stored, refrigerate it to minimize changes in salinity. Storage at room temperature will allow calcium (Ca) and bicarbonate (HCO_3) to precipitate and lower the total salinity level of the water.

READING AN ANALYTICAL REPORT

An analysis of an irrigation water sample or a soil-water sample vacuum-extracted from a saturated soil mea-

Table 7.1 Common laboratory determinations and preferred units in reports of irrigation water quality and soil salinity.

	Reporting symbol	Reporting units	Soil	Water
Saturation percentage	SP	%	Yes	No
Acidity-alkalinity	pH	None	Yes	Yes
Electrical conductivity		dS/m	Yes	Yes
Soil	EC_e	dS/m	Yes	No
Water	EC_w	dS/m	No	Yes
Calcium	Ca^{2+}	meq/L	Yes	Yes
Magnesium	Mg^{2+}	meq/L	Yes	Yes
Sodium	Na^+	meq/L	Yes	Yes
Bicarbonate	HCO_3^-	meq/L	Yes	Yes
Carbonate	CO_3^{2-}	meq/L	Yes	Yes
Chloride	Cl^-	meq/L	Yes	Yes
Sulfate	SO_4^{2-}	meq/L	Yes	Yes
Boron	B	meq/L	Yes	Yes
Nitrate	NO_3^-	meq/L	Yes	Yes
Sodium adsorption ratio	SAR	meq/L	Yes	Yes
Adjusted sodium adsorption ratio	SAR_{adj}	meq/L	No	Yes
Exchangeable sodium percentage	ESP	%	Yes	No
Lime requirement	LR	tons/acre	Yes	No
Gypsum requirement	GR	tons/acre (6-in depth)	Yes	No
Lime percentage	$CaCO_3$	%	Yes	No

sures water-soluble salinity, not exchangeable salinity. Laboratories can analyze exchangeable salinity, but this must be requested and may cost more. Table 7.1 lists the determinations usually provided in an analytical report relating to irrigation water or a soil extract. Analytical results can be lengthy and full of unfamiliar terms. This section will explain what the terms mean.

Terminology and Units

The saturation percentage (SP) is a measure of soil-water content after enough distilled water has been added to saturate the pore space. It is based on the weight of the soil after it has been dried in an oven. SP is useful in that it can help characterize soil texture. Very sandy soils have SP values of less than 20 percent; sandy loam to loam soils have SP values between 20 and 35 percent; and silt loam, clay loam, and clay soils have SP values from 35 to over 50 percent. Also, salinity measured in a saturated soil can be correlated to soil salinity at different soil-water contents measured in the field. As a rule, the soil-water content of a saturated soil is approximately two times higher than the soil-water content at field capacity. Therefore, the soil salinity in a saturation extract will be diluted to one-half the level in the same soil at field capacity.

The pH of a soil or water measures hydrogen ion concentration (activity). Although pH is closely related to the availability of some macro- and micronutrients, it is not a useful measure of salinity.

Most crop tolerance guidelines for salinity are related to electrical conductivity measurements. Electrical conductivity, denoted as EC_e for extracts from soil and EC_w for irrigation water, is a measure of total salinity, but it does not give any indication of the salt composition. Electrical conductivity is measured by placing two electrodes into the saturation extract or irrigation water sample. An electrical current passes between the two electrodes. As the salinity level in the sample increases, the electroconductivity meter detects increasing electrical current and the EC determination increases in value. The preferred reporting unit for EC, deciseimen per meter (dS/m), is now the internationally accepted unit. Until recent years, the most common unit of reporting was millimhos per centimeter (mmhos/cm). This reporting unit is still acceptable and is equal to the unit dS/m.

Occasionally, EC_w values are reported in micromhos per centimeter (µmhos/cm). When EC_w values are reported in µmhos/cm, convert them to dS/m or mmhos/cm to apply crop tolerance guidelines. To convert µmhos/cm to dS/m or mmhos/cm, divide the EC_w value by 1,000.

Another term often found in analytical reports is total dissolved solids (TDS). This term represents the original method of measuring soil and water salinity before electrical conductivity methods were developed. A specific volume of soil-extract or water sample was weighed and then the water was evaporated away. After evaporation, the solids (mostly salts) were weighed again. TDS is expressed in milligrams per liter (mg/L) on analytical reports. Today, TDS has little value in evaluating salinity problems because crop tolerance thresholds are correlated with EC_e and EC_w rather than TDS.

Salts, such as sodium chloride (NaCl) and calcium sulfate ($CaSO_4$), consist of positively charged cations and negatively charged anions bonded together by opposing charges. In irrigation water or soil-water, many of the bonds are broken and the water consists of individual cations and anions. To understand salinity composition, soil-water and irrigation water samples must be analyzed for individual cations and anions. Calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^+) are the predominant cations in soil extracts and irrigation water. Although potassium (K^+) is important as a nutrient, it is usually a very minor component of salinity. Bicarbonate (HCO_3^-), carbonate (CO_3^{2-}), sulfate (SO_4^{2-}), and chloride (Cl^-) are the main anions in most soil extracts and irrigation water. Along with these anions, boron (B) and nitrate (NO_3^-) are anions commonly reported in analytical results. Boron does not contribute significantly to total salinity and the osmotic effects on soil-water availability, but it is important in diagnosing specific ion toxicity. Knowing the NO_3 content of the soil and irrigation water is valuable in making fertilizer decisions, but nitrate does not contribute significantly to salinity.

The preferred unit for reporting individual cations and anions is milliequivalents per liter (meq/L). This unit is used specifically in salinity evaluation and reporting. Most agriculturists who work with pesticides, fertilizers, and tissue analyses are familiar with the reporting units parts per million (ppm) and milligrams per liter (mg/L) but unfamiliar with meq/L. The unit meq/L differs from mg/L in not only denoting the concentration of a specific cation or anion in a soil extract or water sample but also considering the elec-

Table 7.2 Factors to convert milligrams per liter (mg/L[ppm]) to milliequivalents per liter (meq/L).*

Cation or anion	Symbol	Conversion factor
Calcium	Ca^{2+}	20.0
Magnesium	Mg^{2+}	12.0
Sodium	Na^+	23.0
Bicarbonate	HCO_3^-	61.0
Carbonate	CO_3^{2-}	30.0
Chloride	Cl^-	35.5
Sulfate	SO_4^{2-}	48.0

* mg/L ÷ factor = meq/L.

trical charge of the cations and anions. This is important because soils contain negatively charged clay particles in which the adsorption of charged ions to soils (and thus the availability to the trees) is determined not only by concentration but also the electrical charge of the ions. Reporting cation and anion composition in meq/L is one of the hallmarks of a quality laboratory service. Table 7.2 shows how to convert from mg/L to meq/L.

The unadjusted sodium adsorption ratio (SAR), adjusted sodium adsorption ratio (SAR_{adj}), and exchangeable sodium percentage (ESP) are indices calculated from the individual cation and anion determinations. These indices must be used along with the EC values to evaluate salinity and sodicity accurately.

The unadjusted SAR indicates the levels of Na, Ca, and Mg in a soil-water extract or irrigation water sample. An increasing SAR value indicates an increasing fraction of Na in comparison to Ca and Mg. Rising levels of Na reduce soil stability, decrease water infiltration, and increase the likelihood of Na accumulating to toxic levels in leaf tissue. Use the SAR to evaluate sodicity problems rather than Na cation levels alone. More Na can be tolerated in a soil extract or water sample when Ca increases proportionally to Na.

SAR_{adj} is calculated and reported only for water samples. This index predicts the reaction of HCO_3 with Ca when water is applied to the soil. Irrigation water with few HCO_3 or CO_3 anions usually has a low SAR_{adj} that is very similar to its unadjusted SAR. Such water will very slowly dissolve lime from the soil and contribute Ca to offset Na in the soil-water. Irrigation water high in HCO_3 or CO_3 usually has an SAR_{adj} that is higher than its unadjusted SAR. Such water precipitates Ca with HCO_3 and forms lime, which reduces Ca levels in the soil-water and increases the proportion of Na. Prior to 1988, SAR_{adj} was calculated according to an empirical equation using pH constants (pH_c). This has since been proven to overestimate SAR_{adj}. The new procedure is based on the proportion of Ca and HCO_3 in a water sample. If there is any doubt about how the laboratory calculated SAR_{adj} and the lab staff cannot clarify which procedure was used, base the interpretations on the unadjusted SAR alone.

ESP is closely related to SAR. These indices differ in that SAR is an index of the water-soluble Na but ESP is an indicator of exchangeable Na. High ESP indicates that Na is the predominant cation in a soil. Today most laboratories do not measure ESP directly because this would require more costly measurements of the cation exchange capacity and the exchangeable Na content. Instead most laboratories report an estimated ESP based on a correlation between SAR and ESP. Assessing an analysis by considering only SAR does not compromise the interpretation.

Most laboratory reports of soil analysis provide either a gypsum requirement (GR) or a lime requirement (LR). A GR is usually provided for alkaline soils with pH above 7 and SAR above 15. A LR is usually provided for acid soils with pH less than 7. The most common method of determining GR is the Schoonover method. It measure how much Ca must be added in the form of gypsum to replace nearly all the Na on the soil exchange sites.

Verification of Quality

Determine the quality of an analytical report before making a management decision based on it. In a quality report, the cation and anion composition is reported in meq/L. Furthermore, an analysis can be evaluated by (1) checking the cation-anion balance and (2) comparing total salinity, expressed as EC, to the sum of the cations or anions. Table 7.3 is a sample analytical report. The next two paragraphs will refer to it to show how to check the quality of an analysis.

First consider the cation-anion balance method. Salts—such as NaCl, $NaHCO_3$, and $CaSO_4$—consist of cations and anions bonded together by electrical charges. For each cation there is an equivalent charge (amount) of anion bonded to form the salt. This is referred to as the cation-anion balance. When dissolved in a water sample or soil extract, the bonds are broken and the salts exist as individual cations, anions, or neutral ion pairs. For example, in Table 7.3 the sum of the cations (Na, Ca, and Mg) is 10.2 meq/L and the sum of the anions is 10.2 meq/L (HCO_3, CO_3, SO_4, and Cl). The individual cations and ions must be reported in meq/L to perform this check. Omit B and NO_3 in this procedure, because they are reported in mg/L and are a minor component of the total salinity.

Now consider the second procedure, comparing total salinity, expressed as EC, to the sum of either the cations or anions. The salinity level, indicated by EC_w,

Table 7.3 Sample irrigation water quality analysis.

	Reported data
pH	8.4
EC_w	1.0 dS/m
Ca^{2+}	0.5 meq/L
Mg^{2+}	0.1 meq/L
Na^{+}	9.6 meq/L
HCO_3^{-}	4.2 meq/L
CO_3^{2-}	1.0 meq/L
Cl^{-}	4.9 meq/L
SO_4^{2-}	0.1 meq/L
B	0.7 mg/L
NO_3^{-}	5.2 mg/L
SAR	17.5
SAR_{adj}	16.6

multiplied by a factor of 10 will approximate the sum of the cations or anions if the analysis is valid. In the example in Table 7.3, the EC_w is 1.0 dS/m. This value multiplied by 10 suggests the water sample contains about 10 meq/L of assorted cations and 10 meq/L of assorted anions. The sum of the individually measured cations or anions is 10.2 meq/L, which is close to the value calculated from EC_w.

Beware of a report in which the EC multiplied by 10 exactly equals the sum of either the cations or anions. Such a result may indicate that some of the individual cations and anions were estimated by subtraction rather than determined by direct measurement. SO_4 and Na are the most likely elements to be estimated because measuring them requires additional analytical steps and costs.

DIAGNOSING SALINITY

Salinity analyses are used to diagnose three types of salinity conditions in the field: (1) excess root zone salinity, (2) poor water infiltration rates, and (3) accumulation of specific elements to toxic levels.

Excess Salinity

A high EC_e or EC_w value indicates high salinity. Excessive salts reduce soil-water availability, which decreases absorption by roots. Saline soils have a greater capacity to retain water and require trees to exert more energy to absorb water. Trees grown in saline soil may show symptoms of water stress even though the soil may appear or feel as though it contains sufficient soil-water. The trees may display inadequate shoot growth, reduced nut size, and increased incidence of sunburn and kernel shrivel. Necrotic (brown, dead) tissue along leaf tips and margins may indicate excess salt absorption and accumulation.

Table 7.4 provides guidelines for identifying soils and irrigation water supplies whose total salinity is sufficiently excessive to limit walnut production. Salinity research specific to walnut has been limited to young seedling rootstocks. An extensive review of the literature revealed that researchers have not investigated the salinity tolerances of walnut rootstocks grafted to popular walnut scions and grown to maturity. Rather, present guidelines pertaining to the salinity tolerance of walnut are based on field experience with and salinity research regarding similar crops, such as almond and plum.

Table 7.4 Guidelines for evaluating soils and water supplies whose salinity exceeds the tolerance of mature walnut trees.*

Salinity measurement	Unit	Degree of restriction for walnut		
		None	Increasing	Severe
Average root zone	dS/m	<1.5	1.5–4.8	>4.8
Irrigation water	dS/m	<1.1	1.1–3.2	>3.2

*Guidelines assume a 15 percent annual leaching fraction.

The available research and field experience suggest that the salinity tolerance of walnut is similar to that of almond. Walnut growth and production should be unaffected on soils with average root zone salinity of less than 1.5 dS/m when irrigated with water with a salinity below 1.1 dS/m. Both these limits assume that irrigation is managed to provide a 15 percent annual leaching fraction to prevent salt accumulation from underirrigation. (The term *leaching fraction* is defined later in this chapter.) In other words, the amount of water applied must equal the amount lost through seasonal crop evapotranspiration (ET) plus a quantity equaling about 15 percent of seasonal crop ET. If a smaller leaching fraction is achieved, trees can tolerate a lower level of salinity in soil and irrigation water. Research further indicates that, for each 1.0 dS/m increase in average root zone salinity above 1.5 dS/m, the tree growth rate, and perhaps production potential, declines by 18 to 21 percent.

Poor Water Infiltration

Low water intake rates can prevent trees from getting sufficient water and, at the same time, cause insufficient root zone aeration. Symptoms of poor water infiltration include reduce shoot growth; increased incidence of sunburn and kernel shrivel; and frequent problems with disease, such as phytophthora, crown gall, and deep bark canker.

Soils and irrigation water with very low total salinity or a high proportion of Na are likely to develop poor infiltration rates. Both conditions contribute to unstable soil structure; soil aggregates swell and disperse into individual particles when irrigated. After the applied water recedes, the soil particles settle. The fine-

Table 7.5 Guidelines for evaluating infiltration.

SAR	Potential for water infiltration problem	
	Unlikely if EC_e or EC_w	Likely if EC_e or EC_w
0–3	>0.7	<0.3
3.1–6	>1.0	<0.4
6.1–12	>2.0*	<0.5
12.1–20	>3.0*	<1.0
20.1–40	>5.0*	<2.0

*Even though these salinity conditions are unlikely to promote slow infiltration, the EC values exceed levels tolerable to walnut.

textured clay and silt wedge in the pores, between the large sand particles, and the result is a less permeable crust.

To assess infiltration, you must evaluate both salinity and Na composition (sodicity). Total salinity is measured by EC_e or EC_w; the measure of sodicity is the SAR of the sample. Table 7.5 presents guidelines for evaluating these factors. Be aware, however, that the table applies to conditions in the San Joaquin Valley and may not be applicable to all locations in California. Orchards in the Napa Valley and central coast areas contain a large amount of serpentine, for example. As a result, the soil and water in these orchards is rich in Mg and relatively low in Ca. In such an environment Mg may behave like Na, and the result is unstable soil that tends to disperse and become impermeable. Although the diagnostic criteria for such conditions have not been extensively tested, some professional consultants suggest that, when the Mg to Ca ratio exceeds 1:1, serpentine soils may develop infiltration problems. Another soil to which table 7.5 does not apply is one rich in exchangeable K. Some reports maintain that, when K is the predominant cation, it has the same effect on soil stability and porosity as Na does: The soil becomes less stable and more impermeable.

Toxic Accumulations

Toxic ion effects. The accumulation of an ion to the point of toxicity can take several years. In this regard, Na, Cl, and B are the primary ions of concern. Trees grown on soils with an excess of one of these elements accumulate ions in the woody tissue and eventually in the leaves. Leaf burn on leaf margins often means excess Cl or Na in leaf tissue. The margins of foliage containing excess B may develop leaf burn that expands into interveinal necrosis with twisting and curling of the leaves. Accumulation of Na, Cl, or B ions is likely to reduce production of necessary plant hormones and contribute to nutrition disorders.

It is important to diagnose ion accumulation before levels become elevated in the woody and leaf tissue. Once ions accumulate there, the trees have no rapid mechanism to expel them. Correcting the toxicity in the root zone may require several seasons of tree growth, production, and management.

Analysis of salt, irrigation water, and leaf tissue can diagnose conditions in which toxic ion effects are likely to occur. Tables 7.6 through 7.8 provide guidelines for identifying such conditions.

If soil or water analysis indicates an excess of a specific ion but the leaf tissue does not, it may be only a matter of time before the ion accumulates to toxic levels in the trees. The soil or water analysis may reveal a problem before it actually affects production.

Nitrate Nitrogen. Toxicity of nitrate nitrogen (NO_3-N) becomes a concern when too much N fertilizer is applied. If overapplication is severe, the first effect may be foliage that grows so large, in fact, that the leaves curl or appear cup shaped. In severe cases defoliation may occur, but the trees will most likely regrow with tremendous vigor. Use soil and water analyses to avoid overuse of fertilizer and instead achieve highly efficient N management practices.

In irrigation water, a NO_3-N level from 0 to 10 mg/L is considered low, from 10 to 30 mg/L is considered moderately low to moderately high, and a level greater than 30 mg/L is considered high. In a soil sample taken from a depth of 1 foot, a NO_3-N level from 0 to 5 mg/L is considered low; 5 to 15 mg/L, moderately low to moderately high; and a level exceeding 15 mg/L, high.

To convert the level of NO_3-N in a water analysis to pounds of N per acre-foot of water, multiply the NO_3-N concentration reported in mg/L by 2.7. For example, if the analysis reports that a sample of water contains 2.3 mg/L of NO_3-N, the sample contains 6.2 pounds of N per acre-foot of water.

Similarly, you can convert the level of NO_3-N reported in a soil analysis to pounds of N per acre-foot of soil. In the lab report find the level of NO_3-N in a composite sample that represents all samples taken at

Table 7.6 Critical levels of specific ions in saturated soil extract.

Specific ion	Degree of toxicity		
	None	Increasing	Severe
Sodium (SAR)	<5.0	5.0–15.0	>15.0
Chloride (meq/L)	<5.0	5.0–10.0	>10.0
Boron (mg/L)	<0.5	0.5–3.0	>3.0

Table 7.7 Critical levels of specific ions in irrigation water.

Specific ion	Degree of toxicity		
	None	Increasing	Severe
Sodium (SAR)	<3.0	3.0–9.0	>9.0
Chloride (meq/L)	<4.0	4.0–10.0	>10.0
Boron (mg/L)	<0.5	0.5–3.0	>3.0

Table 7.8 Critical levels of specific ions in leaf tissue (July samples).

Specific ion	Degree of toxicity		
	None	Increasing	Severe
Sodium (%)	<0.10	0.10–0.30	>0.30
Chloride (ppm)	<0.30	0.30–0.50	>0.50
Boron (ppm)	<36.00	36.00–200.00	>200.00

a depth of 1 foot—the level is expressed in mg/L. Multiply the mg/L by 4.0. For example, if the analysis reports that the sample contains 9.7 mg/L of NO_3-N, the amount of N in the soil equals 38.8 pounds per acre-foot.

MANAGING SALINITY

The first part of this discussion of salinity management focuses on salinity prevention. It assumes that the orchard has been established on nonsaline soils suitable for walnut production. The goal is to manage the soils and irrigation water to avoid salinity, the accumulation of toxic ions, and the development of slow infiltration rates. The second part of this discussion, in contrast, deals with reclamation, or correcting an existing salinity problem. This discussion assumes that an orchard or potential orchard site has excess salinity, toxic levels of specific ions, poor infiltration rates, or some combination of these problems.

Whether the objective is prevention or reclamation, however, proper management of irrigation water is the key to salinity management. In some situations, application of soil and water amendments will also be an important component of salinity management.

Salinity Prevention through Irrigation and Leaching

Root zone salinity increases when salts or toxic ions are transported into the orchard with irrigation water. The only way of decreasing salinity is transporting salts out of the root zone with deep percolation. This is referred to as leaching, and it is an important function of irrigation.

The leaching fraction is the percentage of the applied water that does not contribute to meeting crop needs. It is expressed as a percentage rather than as a specific quantity so discussions of leaching fraction can be applied to orchards with various water requirements and water qualities.

As the crop ET for walnuts increases or as the concentration of the salts in the water increases, more salinity is transported into the orchard. Therefore, more leaching is required to transport salts beyond the root zone. *Leaching requirement* is the term used when a reduction in the average root zone salinity is desired instead of maintenance of the same level. The leaching requirement is an estimate of the depth of water needed to change a saline soil to a soil with a salinity level tolerable to walnut. It is commonly expressed as inches of water required per foot of soil in the root zone.

Now consider a few general concepts that are germane to effective leaching and salinity control. First, recognize that effective salinity management is easier to achieve in soils with deep, well-drained profiles. A well-drained soil provides a zone for unwanted salts to be transported to—a place to accumulate that is far from the root systems of the trees. Successful leaching for salinity control is much more difficult to achieve on poorly drained soils, because the only place where salts can accumulate is near the root systems. Also consider the effect of the water table. The depth of a shallow water table often fluctuates throughout the season. It is closest to the soil surface in the spring and farthest in the fall. As a result, salinity that may be leached to soil depths in the fall is often transported back into the root zone in the spring, when the water table rises. Growers are well advised to avoid planting walnut in poorly drained soils.

Second, realize that the soil-water content must be recharged to exceed field capacity throughout the root zone before leaching will occur. If it is not, irrigation water in an amount equal to soil-water depletion will be retained in the root zone and will not actually transport salts below the root zone.

Third, recognize that small quantities of irrigation water applied frequently, such as with sprinklers or by winter rainfall, more effectively transport salinity below the root zone than an equal quantity of irrigation water applied in one large flood application. One-time applications of large quantities of water tend to infiltrate and percolate through the larger porous pathways in the soil but fail to transport salinity from the small pores. In practice, leaching is most effectively achieved by winter rainfall and winter irrigations, when evapotranspiration is the lowest.

The last necessary concept concerns the frequency of leaching. Leaching does not have to be accomplished with every irrigation—perhaps not even in every season. The frequency required depends on the specific soil and water conditions. Leaching is necessary only when the average root zone salinity or the level of a specific ion approaches or exceeds the critical level for walnut. This can only be determined by routine soil sampling.

Prevention of Excess Salinity in Soils

Variations in irrigation water quality and soil salinity create the need for different leaching fractions from one orchard to the next. Table 7.9 provides leaching fractions required for irrigation water qualities from 0.5 to 2.0 dS/m to maintain a desirable root zone salinity—that is, one from 1.0 to 1.5 dS/m (below the critical level for walnut). The leaching fraction needed to control root zone salinity within tolerable levels increases as the salinity level in the irrigation water increases.

The example that follows shows how to apply table 7.9. Mature walnut grown in a clean-cultivated orchard consume about 42.0 inches of water annually. The irrigation water supply has an EC_w of 0.75 dS/m, and the goal is to maintain an average root zone salinity (EC_e) of 1.5 dS/m. Table 7.9 reveals that a leaching fraction of 12.0 percent is required for salinity control. This equates to a total seasonal water application of

$$42.2 \text{ in.} \div (1.00 - 0.12) =$$
$$42.2 \text{ in.} \div 0.88 = 47.9 \text{ in.}$$

Of the 47.7 inches, 42.0 inches would be applied to meet crop ET; 5.7 inches would leach salinity below the root zone and maintain the current level of salinity.

Table 7.9 also illustrates that leaching fractions needed with irrigation waters with an electroconductivity (EC_w) greater than 1.0 dS/m are quite high—perhaps unreasonable if the water supply is limited and expensive.

Reclamation

When production is restricted in existing orchards by salinity or when development of new orchards would be adversely affected by the present salt levels, reclamation is needed. Table 7.10 shows the leaching requirements needed to reclaim, to tolerable levels, soils with various degrees of salinity. These guidelines assume the leaching requirement is applied in several small irrigations or rainfalls with periods of drying between each. The guidelines apply to leaching of B, Cl, and Na. If leaching is attempted in one irrigation, with a large application of water, the leaching efficiency will decline and may require up to three times the quantity of water to achieve the same level of reclamation.

The example that follows shows how to apply table 7.10. Suppose a grower has a parcel of land that is being considered for orchard establishment. Laboratory analyses indicate that water of the quality 0.4 dS/m will be used for irrigation and that the average root zone salinity, prior to any land preparation, is 3.0 dS/m. The grower would like to have tolerable soil salinity levels for walnut, at least to a depth of 5 feet. Using table 7.10, the grower learns that to reduce the initial soil salinity to an average of 1.5 dS/m will require about 1.8 inches of water per foot of root zone soil. In other words, the grower must apply a minimum of 9.0 inches of water to this soil when it is at field capacity. Leaching requirements can be extrapolated for salinity levels that fall between levels specified in the table, assuming drainage is sufficient for the leachate to move below the root zone.

The Need for Resampling

Tables 7.9 and 7.10 outline effective irrigation practices to achieve successful salinity management. These guidelines are research-based and the best available, but their effectiveness can only be verified by resampling the soils. Always confirm that the salinity conditions have been improved to the extent the guidelines predict. If conditions have not improved sufficiently, adjust your management practices.

Soil and Water Amendments

Soils with poor infiltration and permeability rates are candidates for treatment with amendments. The amendments supply exchangeable Ca that displaces Na in the soil and, in some instances, Mg and K. Whereas Na (and Mg and K to a lesser degree) causes swelling and dispersion when a soil is irrigated, exchangeable Ca is scientifically proven to stabilize soil aggregates and porosity, which sustains water infiltration and permeability.

Amendments change the soil or irrigation water composition: Rather than being dominated by Na and HCO_3, the soil or water contains an increased amount

Table 7.9 Leaching fraction required to maintain a specific level of root zone salinity (EC_e) with variable levels of salinity (EC_w) in irrigation water.

EC_w (dS/m)	EC_e = 1.0 dS/m (% leaching fraction)	EC_e = 1.5 dS/m (% leaching fraction)
0.50	6.5	4.0
0.75	20.0	12.0
1.00	32.0	25.0
1.25	35.0	28.0
1.50	55.0	40.0
1.75	65.0	43.0
2.00	85.0	55.0

Source: Adapted from Hoffman 1990.

Table 7.10 Irrigation water required for leaching to reduce average root zone salinity to a level tolerable to walnut.*

Average root zone salinity after leaching (dS/m)	Average root zone salinity before leaching (dS/m)†			
	2.0	3.0	4.0	5.0
1.0	1.8	3.0	4.2	5.4
1.5	0.6	1.8	3.0	4.2
2.0	0.0	0.6	1.8	3.0

Source: Adapted from G. J. Hoffman. 1986. Guidelines for reclamation of salt-affected soils. *Applied Agricultural Res.* 1(2):65–72.

*Table is applicable to all irrigation waters less than 1.0 dS/m salinity.

†Data refer to inches of leaching water per foot of root zone.

of Ca and, usually, SO_4. Conditions requiring amendments are indicated by laboratory analyses that have high SAR indices and relatively low EC values. Amendments are usually unnecessary where salinity analyses indicate soils with high EC values and relatively low SAR indices. A favorable composition of Ca relative to Na already exists in these conditions; therefore, leaching may be the most appropriate first step toward correcting the salinity problem.

Application of amendments is not a substitute for irrigation practices that achieve the necessary leaching. Adding amendments improves the salinity composition so infiltration and permeability rates are higher and leaching is more attainable. However, without sufficient leaching after the addition of amendments, average root zone salinity will increase and the displacement and removal of Na (and perhaps of Mg or K) from the root zone will not be completed.

Types of amendments. The two general types of amendments are Ca salts and acid-forming amendments. Sometimes Ca salts are referred to as direct Ca suppliers and the acid-forming amendments are referred to as indirect Ca suppliers.

Ca is added to the soil directly when Ca salts are used as soil amendments. Common Ca salts include gypsum, lime, dolomite, calcium chloride ($CaCl_2$), and calcium nitrate ($Ca(NO_3)_2$). Each salt has a specific solubility rate in water. $Ca(NO_3)_2$ and $CaCl_2$ are highly soluble; gypsum moderately, soluble; and dolomite and lime, very slowly soluble (when pH is greater than 7.2).

Applying the highly soluble salts directly to irrigation water is convenient but, typically, expensive. Gypsum is reasonably simple to add to irrigation water and may be less expensive than $CaCl_2$ and $Ca(NO_3)_2$. As mentioned, lime and dolomite are relatively insoluble in water unless the water is acidic—that is, has a pH less than 7.0. Gypsum, $CaCl_2$, or $Ca(NO_3)_2$ has negligible effects on soil pH; lime or dolomite can increase soil pH when applied to acidic soils.

Sulfur (S), sulfuric acid (H_2SO_4), urea sulfuric acid, ammonium polysulfide, and lime sulfur are some of the more common acid-forming amendments used in salinity management. Since all contain S or H_2SO_4 but no Ca, they supply exchangeable Ca indirectly, by dissolving lime that is native to the soil. The S compounds undergo microbiological reactions that oxidize S to H_2SO_4. The acid dissolves soil-lime to form a Ca salt (gypsum), which then dissolves in the irrigation water to provide exchangeable Ca. The acid materials do not have to undergo the biological reactions. Instead, on application they react immediately with soil-lime. Acid-forming amendments can also increase the availability of Ca in irrigation water by neutralizing HCO_3 and CO_3 that may otherwise react with Ca to form lime precipitates. Since all these amendments form an acid in the soil reaction, they all reduce soil pH if applied in sufficient quantity.

Amendment selection. Selection of a soil amendment is largely dependent on the presence or absence of lime in the soil and the relative costs of the materials. As long as lime is abundant in the soil (particularly the surface soil), consider either a Ca salt or an acid-forming amendment. In such a case the choice of amendment depends largely on cost. When comparing the costs of amendments, remember that you would use a different amount of each. For example, about 1,200 pounds of H_2SO_4 applied to a calcareous soil supplies as much exchangeable Ca as 2,000 pounds of pure gypsum. Table 7.11 cites the various amounts of available amendments needed to supply equal amounts of exchangeable Ca to the soil or Ca to irrigation water.

Another factor influencing the choice of an amendment is the compound that will be added to the root zone. Some amendments add SO_4; other materials add chloride (Cl_2) or NO_3. NO_3 and Cl_2 content will limit how much of these materials can be added. The amount of N should not exceed annual crop needs. The amount of Cl_2 should not accumulate in the soil to the point that walnut cannot tolerate it. There have been no reports of SO_4 accumulating to toxic levels in walnut.

Do not use acid-forming materials when the soil lacks significant amounts of lime. Such a soil is neutral or acid in pH, so the use of Ca salts is appropriate. Lime or dolomite become preferable to gypsum and $CaCl_2$ as the pH becomes more acid, especially as pH decreases below 6.8. Acid-forming amendments may be more effective on very alkaline soils (those with a pH above 8.4) than Ca salts—the acid-forming amendments will reduce soil pH if applied correctly and at very high rates.

Amendment rates for water. Amendments are most often added to water to improve water infiltration into the surface soil. Amendment rates from 1.0 to 3.0 meq Ca/L are considered low to moderate; rates that supply 3.0 to 6.0 meq Ca/L are considered moderate to high. For example, table 7.11 (the far right column) indicates z or 266 pounds of pure sulfuric acid, per acre-foot of water supplies the equivalent of 2.0 meq Ca/L of amendment (assuming that lime is abundant in the surface soil to react with the sulfuric acid). In comparison, an application rate of 936 pounds of pure gypsum, or 532 pounds of pure H_2SO_4, per acre-foot of water amends the irrigation water at a higher rate of 4.0 meq Ca/L.

If a sample of irrigation water were analyzed after it was amended, you would expect an increased EC_w and a decreased SAR. An appropriate water amendment rate modifies water so that evaluation of both EC_w and SAR suggest little or no probability of infiltration problems (see table 7.5).

Amendment rates for soils. Compared to amendment rates for water supplies, those for soils are considerably higher. The purpose of applying a soil amendment is to reduce the exchangeable Na throughout the root zone, not just at the soil surface. For soils that have potential for walnut production, amendment rates may range from 1.0 to 3.0 tons of gypsum, or an equivalent amount of another material, per acre-foot of soil. If higher amendment rates are needed, the soils may be inappropriate and too risky to develop for a salt-sensitive crop like walnut.

The GR determined by the Schoonover method is commonly provided on an analytical report as one method of determining an appropriate soil amendment rate. However, such an estimate often overstates the GR because the method measures how much gypsum is needed to replace all the exchangeable Na adsorbed by a soil. Complete replacement is unnecessary and more expensive. An amount of gypsum, or an equivalent amount of another amendment, that supplies 50 to 75 percent of the stated GR should be sufficient to result in marked improvement.

Methods of Applying Amendments

After selecting an amendment and determining an appropriate rate of application, you must decide the most appropriate method of application. Choices include applying the amendment in the water, applying the amendment to the soil surface and irrigating it into the soil, broadcasting the amendment and tilling it into the soil, and applying the amendment in a band in the soil.

Adding amendments directly to the water is ideal for managing soils with infiltration problems caused by surface crusting. Research has shown that on many soils a crust sufficient to be a barrier to infiltration can be formed by only one irrigation. Such a crust is on the soil surface and is often thinner than 1 inch. Because the crust is created partly by the irrigation water quality, by consistently putting amendments in the water you are applying them at precisely the point where they are most needed. Such a soil needs relatively small amounts of amendment frequently applied, and water

Table 7.11 Amounts of amendment required in calcareous soils to replace 1 meq/L of exchangeable sodium in the soil or to increase the calcium content in the irrigation water by 1 meq/L.

Chemical name	Common or trade name, Composition	Lb/acre required to replace 1 meq/100g exchangeable Na in 6 in. soil	Lb/acre-ft water to obtain 1 meq/L Ca
Sulfur	100% S	321.0	43.6
Calcium polysulfide	Lime-sulfur 23.3% S	1,410.0	192.0
Gypsum	Gypsum 100% $CaSO_4\ 2H_2O$	1,720.0	234.0
Calcium chloride	Electro-Cal 13% calcium	3,076.0	418.0
Potassium thiosulfate	KTS 25% K_2O, 26% S	1,890.0* 3,770.0	256.0 513.0
Ammonium thiosulfate	Thio-Sul 12% N, 26% S	807.0† 2,470.0	110.0 336.0
Ammonium polysulfide	Nitro-Sul 20% N, 40% S	510.0† 1,000.0	69.0 136.0
Monocarbamide dihydrogen sulfate and sulfuric acid	N-Phuric, US-10 10% N, 18% S	1,090.0† 1,780.0	148.0 242.0
Sulfuric acid	100% H_2SO_4	981.0	133.0

Source: Adapted from Kearney Foundation of Soil Science. 1992. *Water penetration problems in California soils: Prevention, diagnosis, and solutions.* Oakland: University of California Division of Agriculture and Natural Resources.

*The lower equivalent rate assumes that Na exchanges with potassium as well as Ca derived from the oxidation of S. The higher equivalent rate assumes Na is only exchanged with Ca occurring from the oxidation of S.

†The lower equivalent rate assumes that nitrification of NH_4 to NO_3 will provide Ca to exchange with Na in addition to Ca derived from the oxidation of S. The higher equivalent rate does not allow for nitrification.

treatment is an easy and accurate way of doing so. Before applying an acid-forming amendment in this situation, be certain that soil-lime is present in the surface soil or that the water contains high levels of Ca and HCO_3.

Broadcasting amendments such as gypsum onto the soil surface and irrigating the amendment into the soil is an alternative to water treatments. The primary advantage to broadcasting is that the gypsum used is less expensive than that used for water treatment. However, for surface applications to be nearly as effective as water treatment, the application has to be properly timed. If infiltration is a problem in the summer months, then the amendment should be applied at the onset of summer and not during the preceding fall or winter. Applying the amendment too early will result in it being moved, by postharvest and winter irrigations and rainfall, to a depth beyond where the crust forms. Surface applications are most effective if applied at rates equivalent to 500 to 1,000 pounds of gypsum per acre monthly during June, July, and August. Using more finely and consistently ground gypsum may be advantageous in this case. Growers often find broadcasting a nuisance and prefer to add amendments to the water.

Land applications of amendments are more appropriate than water applications when the objective is to reclaim a sodic soil in which sodicity is deep in the root zone and not limited to the soil surface. The large applications this situation requires are more affordable if applied on the land. Incorporating the amendment by plowing, shanking, or slip-plowing will speed up reclamation by quickly getting the amendment to the deeper soil so the exchange reaction can occur.

Banding or amending only a small portion of the soil with acid-forming amendments is another method of application. Banding is most appropriate where the objective is to correct a micronutrient deficiency in alkaline soil by lowering soil pH. This is actually a nutrient management practice unrelated to salinity management. Effective rates of sulfuric acid range from 2 to 6 tons of acid per amended acre, depending on the lime content of the soil. However, to avoid crop injury, a one-time application should not exceed 1,000 pounds per acre. Broadcast applications of acids and sulfurs over all the soil are too expensive to apply at a rate that will reduce soil pH, because all the lime must be neutralized before soil pH will decline significantly. Applications to the entire soil surface require 20 tons of pure H_2SO_4 to neutralize 1.0 percent lime content in an acre of soil 1 foot deep. Many calcareous soils have more than 2.0 percent lime content per foot. Application of acid-forming amendments in irrigation water can also be effective as long as water is applied with drip or microjet irrigation. This type of watering limits the volume of soil that is irrigated and concentrates the amendment.

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