A PNW Extension Publication

Managing Salt-affected Soils for Crop Production

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Excess sodium can destroy soil structure and slow water infiltration, as shown in a sodic soil crust.

Credit: Bryan G. Hopkins

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Summary

Salt accumulation in soil can reduce crop yields and irrigation effectiveness, and affect soil structure and other soil properties. The predominant salts that accumulate in soils are calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate and bicarbonate. However, any salt that accumulates in excess amounts in the soil can cause plant growth problems.

Management of salt-affected soils is a challenge because salts affect many processes, including crop growth (yield, quality and economic return), soil physical properties (aggregation and water infiltration), and availability and toxicity of nutrients. Soil testing indicates risk of soil and crop damage from salts.

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There are three types of salt-affected soils:

1. Saline soils contain high concentrations of soluble salts. Soluble salts present in the root zone can make it difficult for plants to extract water from the soil.
2. Sodic soils have too much sodium.
3. Saline-sodic soils have too much sodium and other soluble salts.

Management practices differ for saline, sodic and saline-sodic soils:

- Saline soils are reclaimed by leaching salts below the root zone with the application of low-salt irrigation water. Plants are most susceptible to soil salinity at germination. In some cases, moving salt away from the germinating seed is all that is necessary.
- Sodic soils require the addition of soluble calcium, followed by leaching of sodium. Calcium promotes soil aggregation. Gypsum is the most common material used to supply calcium for sodic soil reclamation. Elemental S is useful for sodic soil reclamation only when the soil contains free lime.
- Saline-sodic soils must be treated for sodicity first. These soils first require calcium additions to correct sodium, followed by leaching to remove salts.

When developing a plan for salt management, keep in mind these concepts:

- Irrigation water can create or worsen salt-affected soil conditions, making irrigation water management important. Test your irrigation water for salt before using.
- Some crops are more sensitive to salts than others, and plant sensitivity varies depending on crop growth stage and weather.
- High concentrations of chloride and boron can reduce crop yield independent of saline or sodic soil conditions.
- Reclamation of salt-affected soils requires adequate drainage. If necessary, improve drainage before attempting reclamation.

This publication is designed to assist in evaluating the kind and amount of salts present in soils and to select appropriate management practices to maintain soil health and crop productivity.

The “For more information” section provides additional resources on this topic. A companion publication, *Managing Irrigation Water Quality for Crop Production,* *(https://catalog.extension.oregonstate.edu/pnw597)* PNW 597, provides additional details on interpretation of irrigation water analyses.

Salts

Salts are composed of positively charged ions (cations) and negatively charged ions (anions). They can be dissolved in water (soluble salts) or be present as solids. Salts in soil can originate from soil parent material; from irrigation water; or from fertilizers, manures, composts or other amendments. The predominant salts that accumulate in soils are calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate and bicarbonate. Any salt that accumulates in excess amounts in soil can cause plant growth problems.

Salts in the root zone can reduce crop yield by making it difficult for roots to extract water from the soil.

Excess sodium causes problems related to soil structure. As sodium percentage increases, so does the risk of dispersion of soil aggregates (Figures 1 and 2).

High concentrations of certain salts in the soil may also be toxic to plants (see “Beyond salt and sodium: Specific ion toxicities”).

Salt is exported from the soil via leaching through the soil profile or by crop removal. Salts accumulate when inputs exceed exports. To successfully manage salts over the long term, inputs and exports must be balanced.

Knowing how much salt you are applying and how much can be removed is critical for long-term management.

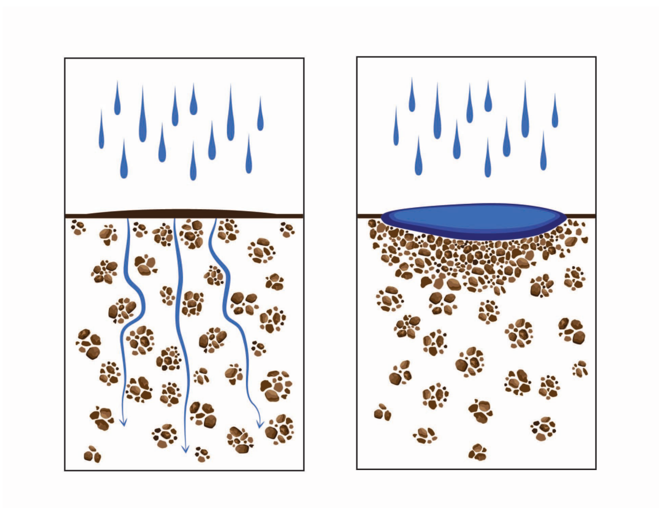

Figure 1. Flocculated (aggregated) vs. dispersed soil structure. Flocculation (left) is important because water moves through large pores, and plant roots grow mainly in pore space. Dispersed clays (right) plug soil pores and impede water movement and soil drainage in all but the sandiest soil.

Credit: James Walworth, University of Arizona

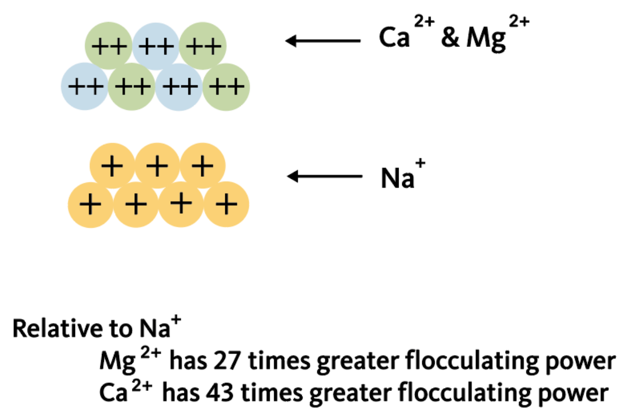

Figure 2. Cations as flocculators. Cations bring together negatively charged clay particles to flocculate soil clays (making clumps or “aggregates”). Sodium (Na^{+}) is a much poorer flocculator than calcium (Ca^{2+}) and magnesium (Mg^{2+}) because it has less charge and because its ionic size in water is much larger.

Credit: James Walworth, University of Arizona

Types of salt-affected soils

Three general categories of salt-affected soils have been identified for management purposes:

- Saline soils: soils affected by salt problems in general.
- Sodic soils: soils affected by sodium problems.
- Saline-sodic soils: soils affected by problems with sodium *and* other salts.

These categories are defined in soil classification literature by the Natural Resources Conservation Service (NRCS) (Table 1). For example, saline soils must have electrical conductivity (EC) above 4 dS/m. Although the NRCS classification is useful for soil surveys, it has limitations for management decisions. For example, many crops are adversely affected at soluble salt values below the NRCS saline soil threshold. See Table 2 and the Glossary for definitions of units and terminology.

Table 1. Classification of salt-affected soils used by the Natural Resources Conservation Service[a]

Salt-affected soil classification	Electrical conductivity (EC)	Sodium adsorption Ratio (SAR)	Exchangeable sodium percentage (ESP)	Typical soil physical condition (soil structure)[b]
None	Below 4	Below 13	Below 15	Flocculated
Saline	Above 4	Below 13	Below 15	Flocculated
Sodic	Below 4	Above 13	Above 15	Dispersed
Saline-sodic	Above 4	Above 13	Above 15	Flocculated

[a] See “Soil testing” for explanations of soil test methods used to describe salt-affected soils.

[b] Soil physical condition (dispersion or flocculation) also depends on factors not included in the NRCS classification system, including soil organic matter, soil texture and the EC of irrigation water.

Similarly, the NRCS classifies the threshold for sodic soils as those with a sodium adsorption ratio (SAR) above 13 or exchangeable sodium percentage (ESP) above 15. Usually, the change from flocculated (aggregated) to dispersed soil structure occurs gradually as sodium level increases. Therefore, you are encouraged to think about salinity and sodicity as continuous variables that affect crop and soil productivity.

Saline soils

The predominant exchangeable cations in saline soils are calcium and magnesium. Saline soils commonly have visible salt deposits on the surface and are sometimes called “white alkali” soils. Most salts in soil solution have a positive effect on soil structure and water infiltration.

Therefore, water penetration is not a major concern with saline soils.

Salts in the root zone can reduce crop yield by making it difficult for roots to extract water from the soil. Salts cause water to move from areas of lower salt concentration (plant tissue) into the soil, where the salt concentration is higher. High salt concentration in the soil can cause plants to wilt even when soil moisture is adequate.

Sodic soils

Sodic soils are high in exchangeable sodium compared to calcium and magnesium. EC is less than 4 dS/m and often less than 2 dS/m.

Soil pH usually is greater than 8.5 and can be as high as 10 or even 11 in extreme cases.

High exchangeable sodium, high pH, and low calcium and magnesium combine to cause the soil to disperse, meaning that individual soil particles act independently. The dispersion of soil particles destroys soil structure and prevents water movement into and through the soil by clogging pore spaces (Figure 2).

Sodic soils often have a black color due to dispersion of organic matter and a greasy or oily-looking surface with little or no vegetative growth. These soils have been called “black alkali” or “slick spots.”

Saline-sodic soils

Saline-sodic soils are high in sodium *and* other salts. They typically have EC greater than 4 dS/m (mmhos/cm), SAR greater than 13, or ESP greater than 15. Soil pH can be above or below 8.5.

Saline-sodic soils generally have good soil structure and adequate water movement through the soil profile.

Soil testing

Soil testing is an important tool for managing salt-affected soils. A laboratory should be able to provide the analyses shown in Table 2.

See "Soil testing questions and answers" for additional information. Equations and detailed explanations of these analyses are given in the Glossary.

Table 2. Suggested soil analyses for assessment of salt-affected soil problems[a]

Analysis	Units	What is measured?	Interpretation of test data
pH	Scale of 0-14	Acidity or alkalinity.	Assesses whether pH is favorable for target crop. Indicates potential solubility of soil minerals and nutrients. One indicator of potential sodic soil conditions.
Electrical conductivity (EC)	dS/m or mmhos/cm	Ability of soil solution to conduct electricity. See Tables 3 and 4 for interpretation.	The higher the EC, the more dissolved ions the soil contains. See Tables 3 and 4 for interpretation.
Exchangeable cations	meq/100 g	Calcium (Ca), magnesium (Mg), potassium (K) and sodium (Na). Concentration of cations that are adsorbed to negatively charged surfaces in soil.	Estimates sodium hazard by calculation of exchangeable sodium percentage (ESP). Estimates gypsum requirement for sodic soil reclamation.
Cation exchange capacity (CEC)	meq/100 g	Capacity of soil to hold positively charged ions (cations).	The higher the CEC, the more gypsum is needed to adjust SAR and ESP.
Specific elements	ppm	Boron (B), chloride (Cl), sodium (Na). Concentration of element in soil solution.	Assesses potential for toxicity of element to plants.
Sodium adsorption ratio (SAR[a])	unitless	Relative concentrations of sodium, magnesium and calcium. Calculated from cation concentrations in a saturated paste extract.	Assesses sodium hazard in soil or irrigation water (Figure 3).
Exchangeable sodium percentage (ESP)[a]	%	Percentage of the total cation exchange sites in soil occupied by sodium.	Sodium hazard increases as ESP increases. The ESP is used to determine gypsum requirement for treatment of sodium-affected soils.

Analysis	Units	What is measured?	Interpretation of test data
Calcium carbonate equivalent	%	Percentage of soil by weight that is undissolved carbonates.	If calcium carbonate is present, it usually is not economical to adjust pH below 8. In this case, acidifying soil amendments such as elemental sulfur or sulfuric acid can be used instead of gypsum for sodic soil reclamation.

[a] A value for exchangeable sodium percentage (ESP) is easily and inexpensively calculated from a routine soil test. If a routine soil test indicates a potential sodium hazard, then the Sodium Adsorption Ratio (SAR) test is recommended. The SAR test is the most accurate test for estimating sodium hazard, but it is more expensive than the ESP test.

Interpretation of soil test results

Table 3 presents the relative risk (low, medium or high) of soil and crop damage from sodium and other salts based on soil analyses. Soils that test "high" have a severe salt or sodium problem. The severity of the problem depends on the crop. Soils with "low" values generally do not have salt or sodium problems.

Soils in the "medium" category must be continually monitored for salt accumulation. Plant expression of sodium and other salt-related problems varies the most in the "medium" range.

See "Glossary" for more information on soil test methods and interpretations.

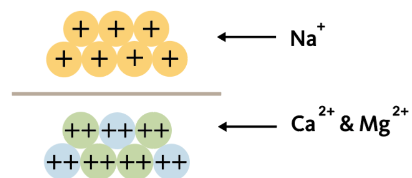

Figure 3. Sodium adsorption ratio (SAR) is a ratio of "bad" (Na) to "good" (Ca and Mg) flocculators. When Na dominates (high SAR), soil disperses, soil pores clog, and water infiltration is limited.

Credit: James Walworth, University of Arizona

Table 3. Relative risk of sodium and other salt problems as determined by soil testing

Soil test measurement	Soil test interpretation (risk of problem)			Problem
	Low	Medium	High	
Electrical conductivity (EC); dS/m or mmhos/cm	Below 1	1–4	Above 4	EC is an indicator of the quantity of dissolved salts. High salt concentrations may reduce seed germination and plant growth. See Table 5 for specific ion toxicities caused by salts.
Exchangeable sodium percentage (ESP)	Below 5%	5%–15%	Above 15%	As ESP increases, soil structure decreases; the infiltration rate of water into soil and the rate of water movement through soil may be reduced. High concentrations of sodium can be toxic to plants.
Sodium adsorption ratio (SAR)	Below 5	5–13	Above 13	Same as ESP
pH	Below 7.5	7.5–8.5	Above 8.5	Soil iron, manganese and copper are less available for plant uptake. If pH is above 8.5, careful monitoring of SAR or ESP is recommended.

Crop tolerance to salinity

Crops vary greatly in their tolerance to salts in the soil solution. How a specific plant responds to salts will depend on soil texture and moisture content as well as environmental conditions such as temperature, humidity and wind speed. Table 4 gives electrical conductivity (soluble salt) values and the resulting expected yield reductions for various crops.

For a sensitive crop such as onions, crop yield can be reduced by 10% when soil EC is 1.8 dS/m and by 50% when EC is 4.3. Barley, a salt-tolerant crop, experiences minimal yield reduction up to an EC of 8.0 dS/m.

Even when salts are below the threshold values listed in Table 4, some crop yield or quality loss may occur. When plants are stressed by other factors — such as drought, extreme weather or herbicides — their tolerance to salts may be reduced. Salt-induced stress at critical growth periods may be more damaging than at other times during the growing season.

Table 4. Electrical conductivity (dS/m) expected to produce a specified percentage yield reduction for selected crops

Crop	Expected yield reduction[a]			
	None	10%	25%	50%
Electrical conductivity (EC), dS/m[b]				
Barley	8.0	10.0	13.0	18.0
Wheat	6.0	7.4	9.5	13.0
Sugarbeet	4.0	4.1	6.8	9.6
Alfalfa	2.0	3.4	5.4	8.8
Potato	1.7	2.5	3.8	5.9
Corn (grain)	1.7	2.5	3.8	5.9
Onion	1.2	1.8	2.8	4.3
Beans	1.0	1.5	2.3	3.6
Apples, pears	1.7	2.3	3.3	4.8
Strawberries	1.0	1.3	1.8	2.5
Sudan grass	2.8	5.1	8.6	14.0
Grapes	1.5	2.5	4.1	6.7
Broccoli	2.8	3.9	5.5	8.2
Cucumbers	2.5	3.3	4.4	6.3

[a] Plant response to salinity depends on growth stage, soil temperature, soil moisture, and other factors. More extensive lists of crop tolerance to salinity are available in resources listed in “For more information.”

[b] EC measured from a saturated paste.

Example: At soil EC of 13.0 dS/m, barley yield is expected to be reduced by 25%. EC measured from a saturated paste.

Beyond salt and sodium: Specific ion toxicities

High concentrations of sodium, chloride, boron or carbonates can reduce crop yield independent of saline or sodic soil conditions. Some research suggests that excessive sodium inhibits plant growth primarily via generalized salt effects, as any salt reduces water availability to plants, rather than via a specific toxicity mechanism.

Crops vary widely in their sensitivity to excess boron, sodium and chloride. For example, blackberries are sensitive to excess boron, showing injury at concentrations above 0.5 ppm (mg/liter) in a saturated paste extract. Tolerant crops such as asparagus can grow without injury at boron concentrations above 6 ppm. More crop tolerance listings are available in “For more information.”

Crops that are sensitive to excess sodium, chloride and boron are most susceptible to damage when irrigation water with high concentrations of these elements is applied to leaves via overhead sprinklers. Crop tolerance to chloride usually is greater when irrigation water is surface applied, avoiding contact with leaves. Drip irrigation is an easy way to accomplish this.

The potential for specific ion toxicities can be diagnosed by testing soil (Table 5) and by testing irrigation water (see *Managing Irrigation Water Quality* (https://catalog.extension.oregonstate.edu/pnw597)). Specific ion toxicities (B, Cl and Na) can be corrected the same way as a salt problem — by leaching salts from the soil using water with low salt concentrations.

Table 5. Relative risk of specific ion toxicity as determined by soil testing

Ion	Units	Relative risk			Plant symptoms from specific ion excess
		Low	Medium	High	
Sodium (Na), Exchangeable sodium percentage (ESP)	%	Below 10%	10–40%	Above 40%	Leaf burn, scorch and dead tissue along the outside edges of leaves
Chloride (Cl)[a]	ppm[b]	Below 175	175–700	Above 700	Wilting, browning of leaf tips, leaf drop
Boron (B)	ppm[b]	Below 0.5	0.5–4	Above 4	Older leaves exhibit yellowing, spotting or drying of leaf tissue at the tips and edges

[a] Values based on chloride toxicity to leaves under sprinkler irrigation. Roots usually are much more tolerant of high chloride concentrations than are leaves.
[b] Parts per million (mg/L) in a saturated paste extract of soil. There is no standard conversion factor from ppm in a saturated paste extract (mg/L) to ppm on a soil dry weight basis (mg/kg). This table is valid only for measurement of ions in a saturated paste extract.

Management of salt-affected soils

Table 6 provides information that is helpful in evaluating problems with salt- affected soils and in identifying appropriate management practices. Long-term data on how a soil has changed over time is essential to making well-informed decisions about irrigation water management, rates and types of soil amendments, and the probability of positive economic returns from managing salt-affected soils.

Once the necessary soil tests and field history have been collected and assessed, the next step is to identify economical options for reclamation. Salt-affected soil reclamation requires management and careful monitoring.

Where sodium and other salt problems are limited to one portion of a field, consider managing that part of the field as a separate management unit. See *Monitoring Soil Units Using a Management Unit Approach,* (https://catalog.extension.oregonstate.edu/pnw570) PNW 570, for suggestions on using a management unit approach.

Salt-affected soil problems do not develop overnight, nor are they solved quickly. It can take years for enough salt to accumulate to reduce crop growth and water infiltration. Reclamation can take just as long. Before undertaking a reclamation program, develop a plan with a knowledgeable consultant. Understanding the implications and costs of a plan is important. In some situations, it is not economical or even possible to reclaim a salt-affected soil.

Table 6. Choosing appropriate management practices for salt-affected soils

Source of information	Description	Evaluation
Potential economic benefit to crop production	What is it worth to prevent or reduce salt problems? If salt problems are corrected or prevented, how much do crop receipts change?	How much can you spend on reclamation and realize a net economic benefit?
Representative soil sample(s) and soil test data	One composite soil sample per management unit. When major visible differences in crop growth or soil properties are present, compare composite samples from separate areas of the field. Ask for a complete analysis from an agricultural soil testing laboratory.	What range of soil test values must your management plan address? Should soil be treated as a saline soil, sodic soil or a saline-sodic soil?
Irrigation water source and quality	Samples from all sources of water used for irrigation.	How much salt, sodium and specific ions are contributed by each water source?
NRCS soil descriptions and soil survey maps	Online soil survey reports provide information on soil depth, restrictive layers, water infiltration rates, drainage class and water-holding capacity.	What are the limitations of the soils for salt or sodium management? What leaching fraction is appropriate?
Aerial photos	Bare soil image or other photography showing distribution of soil characteristics in the field and relative crop growth. Spots of black alkali (sodium) or white alkali (salts) and exposed subsoil are readily seen in a bare soil image.	Should the field be treated uniformly or be broken into management units for salt management?
Onsite drainage assessment	Your observations from tilling, irrigating, planting and harvesting the field. How deep is any hardpan or other restrictive layer? What is the depth to groundwater? Where are the high and low spots in the field? Where does irrigation water puddle?	Where are the problem areas in the field? Does your onsite assessment match soil survey information? Is tile drainage needed to lower the water table?
Typical application rates of fertilizers, composts, manures and other sources of salt or sodium	Amount of each material applied and its chemical analysis.	What is the current loading of salts, sodium and specific ions?

Drainage

There must be drainage to reclaim a sodic, saline or saline-sodic soil. Make sure you have adequate drainage.

Drainage is the unimpeded downward movement of water beyond the crop root zone. It is the ability to move water through and out of the root zone. Hardpans, bedrock and shallow water tables impede drainage.

Signs of poor drainage include surface ponding, slow infiltration or a soil that remains wet for prolonged periods of time. A soil survey map can help determine where fields may have drainage problems. Digging within and below the root zone can also indicate where a drainage problem exists.

In most cases, poor drainage can be solved by breaking up a hardpan with deep tillage. If drainage is impeded by a shallow water table or bedrock, artificial drainage must be installed or another use for the land considered.

Managing saline soils

Leaching

Saline soils irrigated with large quantities of water containing low to moderate levels of salts are reclaimed as the salts leach below the root zone. Initially, reclamation rate depends on the amount of water traveling through the profile and out of the root zone (the leaching fraction). Thus, it is important to ensure that there is adequate drainage in the soil to accommodate an adequate leaching fraction.

When salts come from a shallow water table, the water table must be lowered by providing drainage before reclamation can be accomplished. In some situations, lowering the water table might not be economical, and an alternate crop or land use might be a better choice.

Many saline soils are the result of irrigating with water containing moderate to high levels of salts. Although leaching will minimize salt accumulation, no amount of leaching will entirely correct the problem until an alternate irrigation source is secured to mix with or replace the poor-quality water.

On soils where the best management strategies are used, salts will be lowered to no more than 1.5 times the EC of the irrigation water. The higher the EC of the water used for leaching, the larger the leaching fraction must be to lower soil EC.

Generally, soil salinity (EC) is reduced by one-half for every 6 inches of good-quality water that moves through the soil. Good-quality water has an EC lower than the target for the soil. Thus, if the target zone is 30 inches deep and the EC is 1.5 dS/m, 6 inches of water should flow deeper than 30 inches to reduce the soil EC to 0.75 dS/m. Monitor soil EC following each water application and adjust leaching practices accordingly.

Sandy soils require less management to leach salts because infiltration rates are high and more water can be applied over a shorter period of time. Clays require more management to move salts out of the soil because the infiltration rate is lower and water must be applied more slowly to avoid problems with ponding and runoff.

Other management practices

When good-quality water and adequate drainage are not available, the only option short of abandoning the field may be to select crops tolerant to saline soil conditions. Table 4 shows the expected yield reduction for several crops at various ECs. Use Table 4 to match the salinity level to suitable crops.

Plants are most sensitive to salinity at germination and become more salt-tolerant as they mature. Where germination is the primary concern, leaching all salts out of the root zone usually is neither feasible nor required. Moving salts away from the germinating seed may be all that is needed (Figure 4).

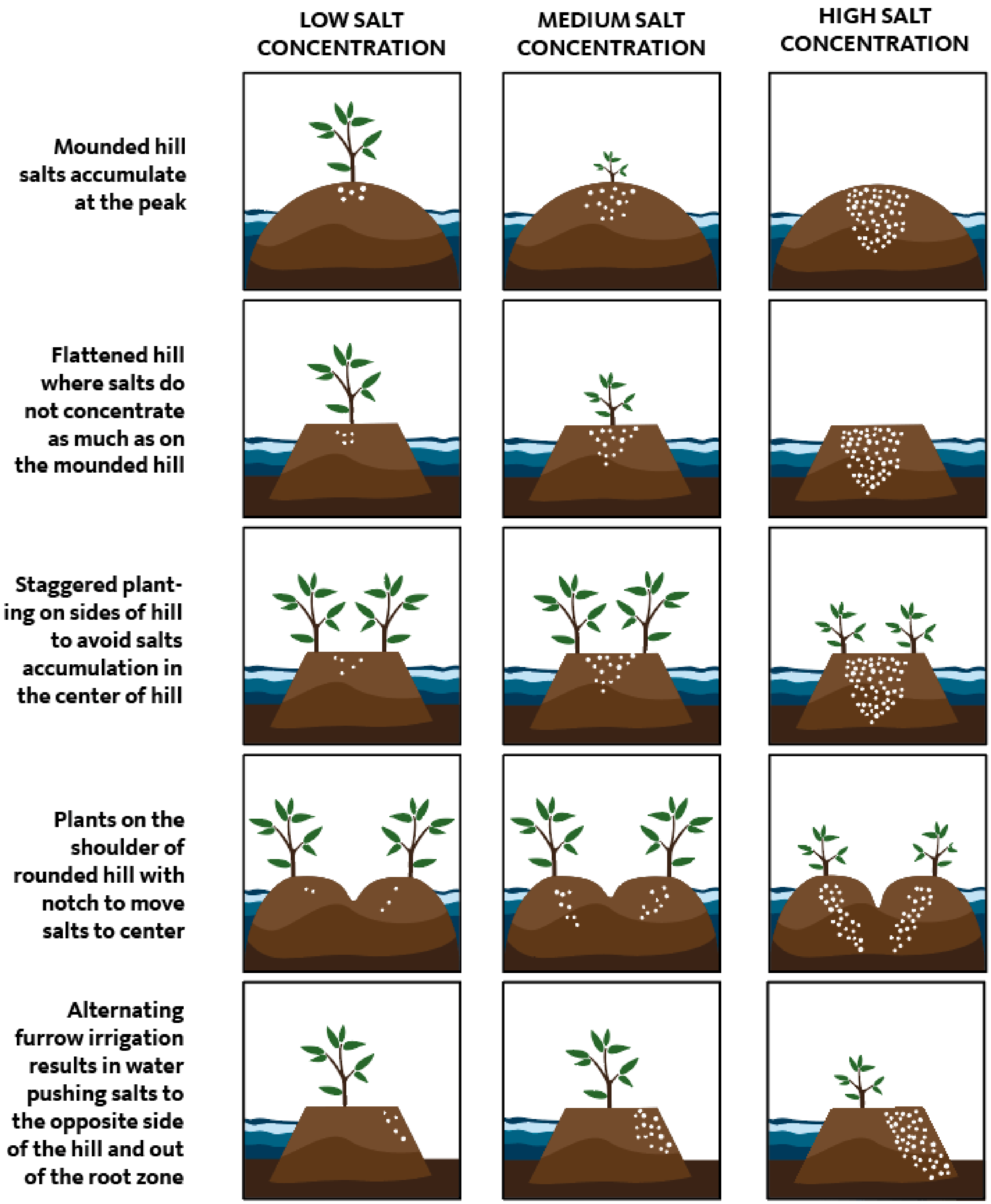

Figure 4. Strategies for moving salts away from germinating seeds in furrow irrigated crops.

Adapted with permission from Treating Irrigated Arid-Land Soils with Acid-Forming Sulphur Compounds. 1979. Technical Bulletin 24. The Sulfur Institute.

Soils can remain productive even where complete reclamation is not possible. These situations require careful management and continual monitoring to ensure acceptable productivity.

Crop growth and harvest will aid in salt removal, improve water penetration, and supply organic matter. Therefore, vegetation management is an important part of reclamation.

Plants have greater difficulty absorbing water under saline conditions. Therefore, saline soil must be maintained at a higher moisture level than nonsaline soil if the crop is to obtain adequate water. This often requires more frequent but lower volume irrigations. Drip irrigation can help to maintain high soil moisture in saline soils.

Soil amendments such as elemental sulfur, gypsum, other calcium materials and other soil amendments do not help reclaim saline soils, despite claims to the contrary. Instead, these materials add salts and compound the problem.

Manures, composts and other soil amendments should be analyzed to determine the types and quantity of salts present. Remember, anything soluble in water will add to the salt load and increase soil EC.

The only way to remediate saline soils is to remove salts from the root zone. This can be accomplished with good drainage and the application of high-quality irrigation water.

Management of sodic soils

Sodic soils usually are the most expensive to reclaim. In many situations, reclamation is not economical. The reclamation procedures discussed here can improve sodic soils, but many years or decades of good soil and crop management are required to fully remediate a sodic soil.

Drainage

Soils with sodicity problems must have drainage to facilitate sodium removal from the root zone. When a high water table is present, it must be lowered before reclamation can proceed. Drainage can be improved by altering the topography or by installing tile drains. Drainage can be improved in some cases by planting deep-rooted perennials such as alfalfa. It is crucial to maintain permeability. When irrigation canal seepage is the cause of high water, the canal water must be intercepted before it enters the field, or the canal must be sealed to reduce seepage.

Tillage and amendments

Tillage often is necessary to physically break up sodium-rich layers and mix amendments into the soil. Coarse organic materials that decompose slowly, such as straw, cornstalks, sawdust or wood shavings used for animal bedding, can help improve soil structure and infiltration when used with other reclamation practices.

Supplying calcium to improve water infiltration

Improving water infiltration rates in sodic soils requires increasing soil electrical conductivity to more than 4 dS/m (4 mmhos/cm) or reducing the exchangeable sodium percentage (ESP). The ESP required for improved water infiltration depends on soil texture and irrigation method. Soils with high amounts of sand can tolerate ESP up to 12 and still retain water infiltration and percolation properties. Soils that are sprinkler irrigated typically require a lower ESP for good water infiltration, compared to soils irrigated with surface irrigation systems.

Soluble calcium is required for sodic soil reclamation, as it will displace sodium and reduce the ESP and SAR (Figure 5). If possible, use irrigation water that is high in calcium and salinity during the initial phase of reclamation.

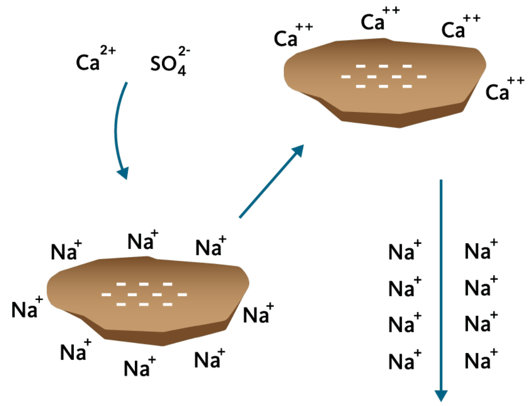

Figure 5. Apply a source of calcium, such as gypsum, before leaching salts out of soils susceptible to dispersion. Replacing sodium with calcium before leaching will stabilize soil structure.

Credit: James Walworth, University of Arizona

Table 7. Gypsum and elemental sulfur (S) required to reclaim sodic soils (0–12-inch depth)

	Amendment rate (ton/acre)	
Exchangeable Na to be replaced by Ca (meq/100 g soil)	**Gypsum**	**Elemental S[a]**
1	1.8	0.32
2	3.4	0.64
4	6.9	1.28
8	13.7	2.56

[a]Elemental sulfur does not supply calcium, but it will dissolve calcium-bearing minerals present in some alkaline soils.

Injecting gypsum (calcium sulfate) into irrigation water increases salinity and calcium. As the sodium is replaced, water lower in calcium and salinity can be used.

Gypsum is the most common material used to supply calcium for sodic soil reclamation. The “gypsum requirement” is the amount of gypsum needed to reclaim the soil to a specified depth. General rates for gypsum application are shown in Table 7. One ton per acre is a minimum application rate. See “gypsum requirement” in the Glossary for how to calculate the gypsum requirement for a specific soil. Using table 7 requires a soil test value for exchangeable sodium.

Gypsum is used because it is calcium-rich, dissolves at high pH, and does not contain elements or compounds that might interfere with reclamation. The sulfate in gypsum is not likely to be a problem for crops, even though it is applied in quantities in excess of plant requirements.

Calcium nitrate or calcium chloride minerals can be used to reclaim sodic soils, but they can be more costly and are likely to produce other negative effects on plant growth or to the environment. Nitrate is considered a groundwater contaminant and is not a good choice. Calcium chloride applied at the typical rates needed for remediation will likely cause chloride toxicity.

Limestone is another commonly available soil amendment that contains calcium. However, it is not used for reclaiming sodic soils because it is not soluble at the high pH levels common in these soils.

Elemental sulfur (S) can be used for sodic soil reclamation in cases where free lime already exists in the soil. The addition of sulfur does not directly add calcium to the soil. However, elemental sulfur oxidizes to form sulfuric acid, which dissolves lime (calcium carbonate), which often exists in arid and semiarid zone soils. The dissolution of indigenous lime provides the calcium necessary to reclaim a sodic soil. When adequate moisture and temperatures are present, oxidation of elemental sulfur will be completed within one or two growing seasons. For more information on soil acidification techniques, see *Acidifying Soil for Crop Production: Inland Pacific Northwest, (https://catalog.extension.oregonstate.edu/pnw599)* PNW 599.

Soil amendments such as elemental S should be incorporated to increase the rate of reaction and to speed reclamation. When elemental S is left on the soil surface, or when the soil is dry or cold, microbial conversion of elemental S to sulfuric acid is delayed.

Table 7 shows the amount of elemental sulfur needed for reclamation based on sodium concentration and reclamation depth. Where available and economical, addition of acids directly to the soil accomplishes the same effect as elemental S, but specialized equipment is required due to safety concerns. Before using elemental sulfur or acids, verify that the soil contains sufficient lime to be dissolved.

Calculating amendment rates for reclamation of sodic soils

Sometimes it is more economical to use materials other than elemental S or gypsum to reclaim a sodic soil. The example below shows how to use Tables 7 and 8 to calculate amendment application rates that supply equivalent amounts of calcium. Elemental S is used as the reference material.

SITUATION
You have a sodic soil with exchangeable sodium soil test value (12-inch depth) of 4 meq Na/100 g.

QUESTION
How much sulfuric acid (tons/acre) is required for reclamation?

CALCULATION
Step 1. Find the elemental S requirement for reclamation in Table 7.
Answer. 1.28 ton elemental S per acre-foot of soil.

Step 2. Find the sulfuric acid equivalency value in Table 8.
Answer. 1 ton elemental S = 3.06 tons sulfuric acid

Step 3. Multiply the elemental S requirement by the sulfuric acid equivalency value to find the amount of sulfuric acid needed.
Answer. 1.28 ton elemental S/acre x 3.06 = 3.9 tons sulfuric acid/acre

Table 8. Equivalent rates of amendments for reclaiming sodic soils

Amendment	Amount of amendment in tons equivalent to 1 ton of elemental S
Gypsum	5.38
Lime-sulfur solution, 25% sulfur	4.17
Sulfur (soil must contain lime)*	1
Sulfuric acid (soil must contain lime)*	3.06
Iron sulfate (soil must contain lime)*	8.69
Aluminum sulfate (soil must contain lime)*	6.94

*Sulfur, sulfuric acid, iron sulfate and aluminum sulfate do not supply calcium. They are useful for reclamation only when the soil contains lime. When the soil to be reclaimed does not contain lime, use gypsum or another material that contains calcium.

Irrigation water management

Some irrigation waters, typically those pumped from deep wells, contain high concentrations of bicarbonate and have a high SAR (high concentration of sodium relative to calcium + magnesium). Application of these waters can create sodic soils over time. Both the EC and the SAR of the irrigation water determine the effect of water application on soil structure and the potential for water infiltration problems.

Irrigation water that is high in bicarbonate or carbonate can react with calcium in the soil solution to form calcium carbonate. This process removes calcium from the soil solution. As calcium in the soil solution is reduced, soil SAR and sodium hazard increase. Precipitation of calcium carbonate in pore spaces also reduces water infiltration and percolation in soils that are not tilled.

The most effective means of avoiding this problem is to acidify the irrigation water prior to application. When an acid such as sulfuric acid is added to irrigation water, it reacts with bicarbonates to form water and carbon dioxide.

For more information on monitoring and managing irrigation water quality, see *Managing Irrigation Water Quality for Crop Production in the Pacific Northwest,* *(https://catalog.extension.oregonstate.edu/pnw597)* PNW 597.

Management of saline-sodic soils

Saline-sodic soils *must* be treated as sodic soils first. These soils require calcium to correct a sodium problem, followed by leaching to remove salts (Table 9). It is important to know how much of a sodium problem exists before applying clean water to leach salts.

High EC irrigation water and soil helps maintain soil structure, increase water infiltration and prevent sodium from dispersing soil particles. However, except for its positive effect on soil structure, high EC (salt) irrigation water is not beneficial for crop production.

Saline-sodic soils often are caused by factors beyond the landowner's control. Many of these soils are the result of natural events, and no amount of reclamation will return them to a satisfactory level of productivity. Under these conditions, use tolerant vegetation such as some grasses to maintain soil cover.

Table 9. Reclamation failures

Goal	Action	Unrecognized problem	Unforeseen outcome
Solve problem of excess sodium in soil.	Add gypsum.	Salts can't be leached from the root zone.	Gypsum (a salt) accumulates. Soil becomes more saline.
Solve problem of excess sodium in a calcareous soil.	Add elemental S.	Salts can't be leached from the root zone.	Gypsum (a salt) accumulates. Soil becomes more saline.
Target: Decrease pH from 7.5 to 7.0.	Add elemental S.	Too much elemental S added.	Soil pH drops to 4.5. Soil is now too acidic for crop.
Remove salts from a saline soil that contains a significant amount of sodium.	Irrigate with low-EC irrigation water to remove salts.	Soil also contains high levels of sodium.	As salts are removed, the remaining sodium causes soil aggregates to disperse, sealing the soil surface. Irrigation water penetrates slowly. Crop growth is reduced.

Soil testing questions and answers

Which laboratory should I use? We recommend choosing a laboratory that uses standard methods for western soils (Table 2).

Does it make a difference if the laboratory uses a fixed extraction ratio (1 part soil to 1 part water) or a saturated paste extract? Most laboratories use a 1:1 or 1:2 soil:water extraction ratio for routine determination of soil pH, soluble salts (electrical conductivity, EC), and exchangeable cations (Ca, Mg, Na, K). Soil pH and EC values determined using a 1:1 or 1:2 ratio are acceptable when salts and sodium are low (Table 3).

When EC is greater than 2 dS/m, or the exchangeable sodium percentage (ESP) is above 5%, we recommend the more accurate (but more expensive) saturated paste method. Management recommendations for salt-affected soils are based on soil test values determined via the saturated paste method.

The saturated paste extract can be used to determine EC, pH, sodium adsorption ratio (SAR), potentially toxic elements (boron, chloride, sodium) and carbonates.

What is the difference between a sodium adsorption ratio (SAR) and an exchangeable sodium percentage (ESP)? Is this the same soil test? SAR and ESP are both used to assess sodium problems, but they are not identical. SAR is measured in irrigation water or in the soil solution using a saturated paste extract. SAR yields information on irrigation water hazard and the amount of sodium in the soil solution (sodium hazard). As the concentration of sodium in soil solution increases, the risk of soil structure destruction by excess sodium increases.

The ESP test is preferred over SAR when the goal is to determine how much gypsum to apply to ameliorate a sodium problem. Gypsum requirement cannot be determined using SAR. To convert SAR to ESP, use the following equation:

$$ESP = [1.475 \times SAR] / [1+(0.0147 \times SAR)]$$

My laboratory reports in different units than those used in this publication. How do I convert units? Use Table 10 to convert test values to other units. Analyses for pH, ESP and SAR are unitless and do not require conversion.

Table 10. Unit conversion factors for irrigation water and soil analyses

Component*	To convert	Multiply by	To obtain
Irrigation water			
Concentration of nutrient in water	mg/L	1.0	ppm in water
Electrical conductivity (EC)	EC (dS/m)	640	Total dissolved solids (TDS) (mg/L)
Application rate	acre-inch	27,150	Gallons
Soil			
Concentration of nutrient in soil	mg/kg or µg/g	1.0	ppm in soil
Electrical conductivity (EC)	dS/m	1.0	mmhos/cm
Electrical conductivity (EC)	mmhos/cm	1,000	µmhos/cm
Sodium (Na)	ppm	0.00435	meq/100 g soil
Calcium (Ca)	ppm	0.0050	meq/100 g soil
Magnesium (Mg)	ppm	0.0083	meq/100 g soil
Sodium (Na)	meq/100 g soil	230	ppm
Magnesium (Mg)	meq/100 g soil	120	ppm
Calcium (Ca)	meq/100 g soil	200	ppm
Cation exchange capacity (CEC), or exchangeable cation concentrations	meq/100 g soil	1.0	cmol (+)/kg

*The same units are used for nutrient and salt concentrations in irrigation water or in water extracted from soil via the saturated paste method.

Glossary

1:1 or 1:2 soil solution: 1 part water is added to 1 or 2 parts soil (weight:weight) in order to measure pH or electrical conductivity.

Acidic soil: Soil with a pH below 7.

Alkaline soil: Soil with a pH above 7.

Anion: A negatively charged ion such as chloride (Cl^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}) or bicarbonate (HCO_3^-).

Cation: A positively charged ion such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^+), potassium (K^+), or ammonium (NH_4^+).

Cation exchange capacity (CEC): A measure of the net negative charge of a soil. Measured as the total quantity of cations that can be exchanged on a unit of soil material, expressed as milliequivalents per 100 grams of soil (meq/100 g), millimoles of charge per kilogram of soil (mmol [+ charge]/kg) or centimoles of charge per kilogram of soil (cmol [+ charge]/kg).

Dispersion: Breaking up of "clumps" of soil particles or aggregates into individual soil particles (sand, silt, and clay). Soil aggregates form larger, more continuous soil pores than do individual soil particles. The larger pores provide better water and air movement.

Drainage: Unimpeded downward movement of water beyond the root zone.

Electrical conductivity (EC): The ease with which electrical current passes through water. EC is proportional to the salt concentration in the water. Consequently, total salt concentration in a soil or irrigation water can be estimated by measuring EC. The higher the EC, the greater the salt concentration.

Elemental sulfur (S^0): A yellow, inert crystalline mineral that is finely ground. In soil, elemental S is oxidized to sulfuric acid via microbial activity. The rate of elemental S oxidation in soil is most rapid in warm, moist soils. Complete oxidation of elemental S to sulfate often takes one to several years.

Evapotranspiration (ET): Combined water use by plants and water evaporated from the soil surface in a given time period. ET usually is expressed as inches or millimeters of water per day.

Exchangeable sodium percentage (ESP): Percentage of the cation exchange capacity that is filled by sodium. It is calculated as:

ESP = [Na^+, meq/100 g soil / CEC, meq/100g soil] x 100

To convert SAR to ESP, use the following equation:

ESP = (1.475 x SAR) / [1+ (0.0147 x SAR)]

Flocculation: The joining together of smaller individual particles of soil, especially clay, into larger units or flocs.

Gypsum: $CaSO_4 \cdot 2H_2O$, the common name for calcium sulfate. Applied as a source of calcium to reclaim sodic and saline-sodic soils.

Gypsum requirement (GR): The approximate amount of gypsum needed per acre to lower the ESP of the soil to a desired level. It is calculated as:

GR = (present ESP – desired ESP) x CEC x 0.021.

The factor of 0.021 assumes CEC is in meq/100 g or cmol (+charge)/kg units. If CEC is in mmols (+ charge)/kg, the factor is 0.0021. These factors assume 90% reclamation efficiency and a desirable SAR in the irrigation water.

Infiltration: Entry of water into soil.

Leaching: The downward movement of soluble ions in the soil profile.

Leaching fraction: The fraction of infiltrated irrigation water that percolates below the root zone.

Leaching requirement: The leaching fraction necessary to keep soil salinity, chloride or sodium (whichever is the most limiting factor) from exceeding a tolerance level for the crop rotation. Leaching requirement refers to long-term average conditions.

meq/L: Milliequivalents per liter.

Perched water table: A shallow water table formed above a soil layer impermeable to water.

pH: A measure of the acidity or basicity of a material or solution. Below 7 is acidic, above 7 is basic, and 7 is neutral.

ppm: Parts per million. Also expressed as mg/kg in a solid matrix or mg/liter in solution.

Saturated soil paste: A reference-state mixture of soil and water used for measuring EC, SAR and pH. At saturation, the soil glistens slightly as it reflects light, flows slowly when the container is tipped, and slides freely and cleanly from a spatula.

Sodium adsorption ratio (SAR): The SAR of a saturated paste extract or irrigation water is a relationship between the concentrations of sodium (Na^+) and calcium + magnesium (Ca^{2+} + Mg^{2+}). SAR reflects the Na^+ status of the soil cation exchange complex. It is calculated as:

SAR = [Na^+] / the square root of 0.5 ([Ca^{2+}] + [Mg^{2+}])

where calcium, magnesium and sodium concentrations are expressed in units of milliequivalents per liter (meq/L).

Soil structure: The combination or arrangement of primary soil particles into secondary particles or units, often called aggregates.

Soil texture: The relative proportion (percent) of the three soil separates (sand, silt and clay) in a soil.

For more information

Extension and outreach publications

- *Drip Irrigation Salinity Management for Row Crops,* (https://anrcatalog.ucanr.edu) Publication 8847. 2011. University of California.
- *Monitoring Soil Nutrients Using a Management Unit Approach,* (https://catalog.extension.oregonstate.edu/pnw570) PNW 570. 2003.
- *Managing Irrigation Water Quality for Crop Production,* (https://catalog.extension.oregonstate.edu/pnw597) PNW 597. 2007.
- *Acidifying Soil for Crop Production: Inland Pacific Northwest,* (https://catalog.extension.oregonstate.edu/pnw599) PNW 599.

- *Soil Structure: The Roles of Sodium and Salts,* (https://repository.arizona.edu/handle/10150/225911) Publication 1414. University of Arizona Cooperative Extension.
- *Monitoring Soil Nutrients Using a Management Unit Approach,* (https://catalog.extension.oregonstate.edu/pnw570) PNW 570. 2003.

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Website

- North American Proficiency Testing Program. (https://www.naptprogram.org) Quality control/quality assurance program for soil, plant and water samples.

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