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MANAGING SALT-AFFECTED SOILS for Crop Production

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Managing Salt-affected Soils for Crop Production

Accumulation of excessive salt in irrigated soils can reduce crop yields, reduce the effectiveness of irrigation, ruin soil structure, and affect other soil properties. This publication is designed to help you evaluate the kind and amount of salts present in soils and to select management alternatives.

This publication describes the soil tests commonly used in evaluating salt-affected soils in the western U.S. and gives general guidelines for test interpretation. It will help you do the following:

- Understand how sodium, calcium, and magnesium affect soil structure
- Request appropriate soil analyses from commercial laboratories
- Interpret soil test data
- Choose appropriate practices for maintaining productivity in salt-affected soils, including:
  - Leaching
  - Amendments (kind and rate)
  - Crop selection
  - Cultural practices (e.g., tillage and bed shaping to improve seed germination)
- Estimate costs and benefits of management practices

Successful salt management requires frequent monitoring of both soil and irrigation water. This publication focuses on soil management, while a companion publication, *Managing Irrigation Water Quality for Crop Production in the Pacific Northwest* (PNW 597-E), addresses irrigation water management for salt-affected soils.

Management of salt-affected soils is a challenge, because salts affect many processes:

- Crop growth (including yield, quality, and economic return)
- Soil physical properties (such as aggregation and water infiltration)
- Sufficiency and toxicity of nutrients

A practice designed to address a single issue might adversely affect other processes (see “Reclamation failures,” page 16). As you read this publication, we encourage you to think about the connections among different aspects of salt management. Consider the potential for unintended consequences when making management decisions.

Because many factors are involved in successful management of salt-affected soils, we recommend that you work with a qualified consultant in designing a management program. Additional resources for management of salt-affected soils are found in “For more information” (page 21).

This publication focuses mainly on practices for irrigated cropping systems. Discussion of management practices for saline seeps in dryland areas is found in McCauley and Jones, 2005 (see “For more information”).

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

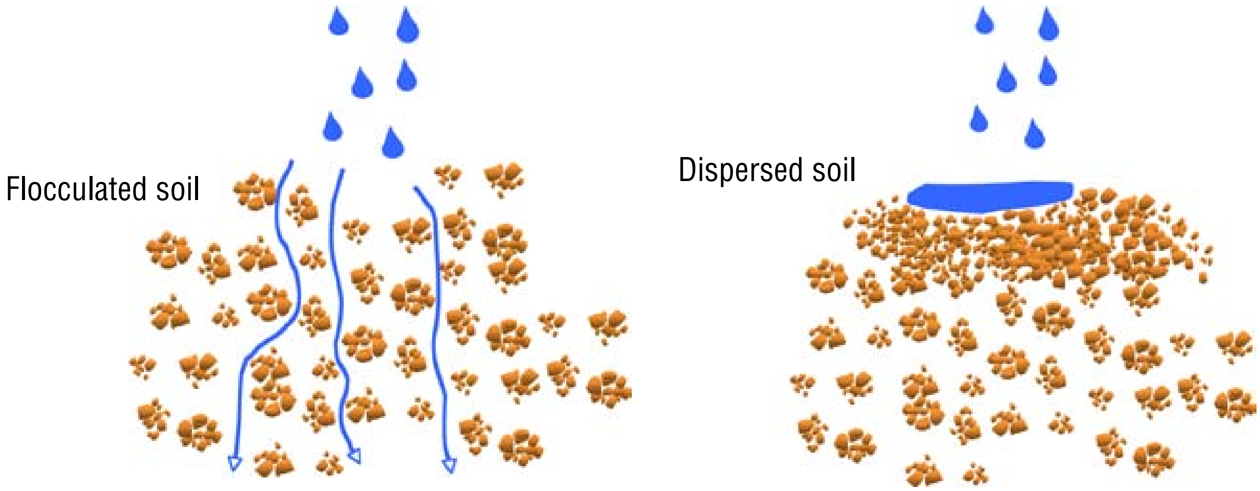

Figure 1.—The difference between flocculated (aggregated) and dispersed soil structure. Flocculation (left) is important because water moves through large pores and plant roots grow mainly in pore space. Dispersed clays (right) plug soil pores and impede water movement and soil drainage in all but the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

predominant salts that accumulate in soils are calcium, magnesium, sodium, potassium, sulfate, chloride, carbonate, and bicarbonate. Any salt that accumulates in excessive amounts in soil can cause plant growth problems.

Too much sodium causes problems related to soil structure. As sodium percentage increases, so does the risk of dispersion of soil aggregates (see 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," page 6).

Salt is exported from the soil via leaching through the soil profile or by crop removal. Salts accumulate when inputs exceed outputs. To successfully manage salts over the long term, inputs and outputs must be balanced. Knowing how much salt you are applying and how much can be removed via leaching is critical to long-term management.

Kinds of salt-affected soils

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

- Saline soils: Salt problems in general
- Sodic soils: Sodium problems
- Saline-sodic soils: Problems with sodium *and* other salts

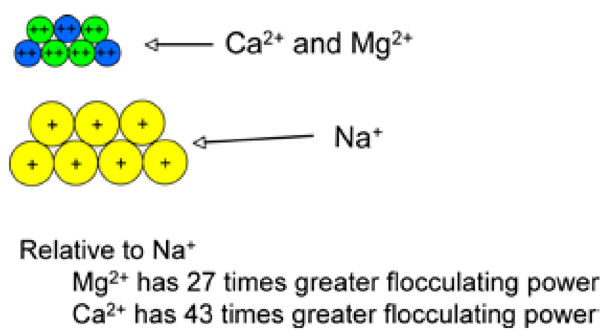

Figure 2.—Cations as flocculators. Cations bring together negatively charged clay particles to flocculate soil clays (making clumps or "aggregates"). Sodium (Na) is a much poorer flocculator than calcium (Ca) and magnesium (Mg) because it has less charge and because its ionic size in water is much larger.

These categories are defined in soil classification literature by the Natural Resources Conservation Service (Table 1, page 3) using defined numerical criteria (e.g., 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.

Table 1. Classification of salt-affected soils used by the Natural Resources Conservation Service (NRCS).[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” (page 4) 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 classification threshold for sodic soils (sodium adsorption ratio above 13 or exchangeable sodium percentage above 15) is somewhat arbitrary. 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 increase soil osmotic potential, causing 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, and/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. They can have the characteristics of either a saline or sodic soil, depending on whether sodium or calcium dominates.

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" (page 17) for additional information. Equations and detailed explanations of these analyses are given in the Glossary (page 19).

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

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.	The higher the EC, the more dissolved ions the soil contains.
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.
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)	unitless number	Relative concentrations of sodium, magnesium, and calcium. Calculated from cation concentrations in a saturated paste extract.	Assesses sodium hazard in soil or irrigation water. (See Figure 3, page 5).
Exchangeable sodium percentage (ESP)	%	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.
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.
Calcium carbonate equivalent	%	Percentage of soil by weight that is undissolved limestone.	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.

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 and/or sodium problem. The severity of the problem is very crop-dependent. Soils with "low" values generally do not have salt or sodium problems.

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

When pH is above 8.5, a soil should be monitored for sodium and other salt accumulation, since a pH above 8.5 indicates sodium problems.

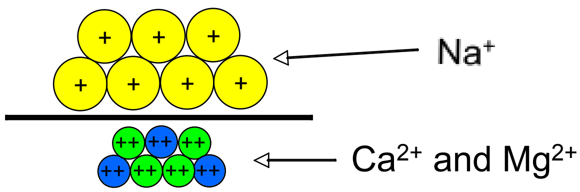

Figure 3.—Sodium adsorption ratio (SAR). SAR is a ratio of "bad" (Na) to "good" (Ca and Mg) flocculators. When Na dominates (high SAR), soil pores clog (soil disperses), limiting water infiltration.

Crop tolerance to salinity

Some crops are very sensitive to salts in the soil solution, while others can tolerate much higher concentrations. How a specific plant responds to salts will depend on soil texture

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

	Soil test interpretation (risk of problem)			
Soil test measurement[a]	**Low**	**Medium**	**High**	**Problem**
Electrical conductivity (EC); dS/m or mmhos/cm	below 0.75	0.75–4	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 (page 7) for specific ion toxicities caused by salts.
Exchangeable sodium percentage (ESP)	below 5%	5–15%	above 15%	As ESP (sodium) 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 above.
pH	below 7.5	7.5–8.5	above 8.5	Soil iron, manganese, and other micronutrients are less available for plant uptake. If pH is above 8.5, careful monitoring of SAR or ESP is recommended.

[a] See the Glossary (page 19) for more information on soil test methods and interpretations.

and moisture content as well as environmental conditions such as temperature 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 percent when soil EC is 1.8 dS/m and by 50 percent 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 (e.g., drought, extreme weather, herbicides), they may not be as tolerant to salts. Salt-induced stress at critical growth periods for the crop may be more damaging than at other times during the growing season.

Beyond salt and sodium: Specific ion toxicities

Individual ions in salt-affected soils can be toxic to plants via other mechanisms in addition to osmotic effects. High concentrations of sodium, chloride, boron, and/or carbonates can reduce crop yield independent of saline and/or sodic soil conditions. Some research suggests that sodium inhibits plant growth primarily via generalized salt effects (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 very 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

Table 4. Electrical conductivity 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

***Example:* At soil EC of 13.0 dS/m, barley yield is expected to be reduced by 25 percent.**

[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" (page 21).

[b] EC measured from a saturated paste.

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
Carbonate (CO_3^{2-}) plus bicarbonate (HCO_3^-)	ppm[b]	Difficult to interpret[c]			Leaves turn yellow between leaf veins due to iron or zinc deficiency

[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.

[c] Although carbonate + bicarbonate analyses are difficult to interpret, this analysis often is offered as part of a complete analysis package. Consult your agronomist for interpretation.

without injury at boron concentrations above 6 ppm. More crop tolerance listings are available in “For more information” (page 21).

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. Chloride tolerance 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 using the saturated paste method (Table 5) or by testing irrigation water (see *Managing Irrigation Water Quality*). Specific ion toxicities are corrected the same way as a salt problem—by leaching high-quality water through the soil.

Management of salt-affected soils

Table 6 (page 8) provides information that is helpful in evaluating problems with salt-affected soils and in identifying appropriate management practices. Having 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 test and field history has been collected and assessed, the next step is to identify economical options for reclamation. Salt-affected soils will need management and careful monitoring to achieve reclamation.

Table 6. Information that can assist in 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, take separate composite samples from good and bad areas of the field for comparison. 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	Soil survey reports provide information on soil depth, restrictive layers, water infiltration rates, drainage class, and water-holding capacity. Reports for irrigated areas generally are available online from NRCS.	What are the limitations of the soils present 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/or 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 the 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 and/or sodium	Amount of each material applied and its chemical analysis.	What is the current loading of salts, sodium, and specific ions?

Where sodium and/or other salt problems are limited to one portion of a field, consider managing that part of the field as a separate management unit. See PNW 570-E 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 salt to accumulate enough to reduce crop growth and/or 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.

Management of 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 needs to be to lower soil EC.

As a general rule, soil salinity (EC) is reduced by one-half for every 6 inches of good-quality water (an EC lower than the target for the soil) that moves through 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.

Drainage

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

What is drainage? How do I make sure I have it? What can I do to improve it?

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 might need to be considered.

Coarser textured (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. Fine-textured soils (clays) require more management to move salts out of the soil because the infiltration rate is lower and less water can be added at one time, potentially creating problems with ponding and runoff.

Other management practices

When good-quality water and/or 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 (page 6) shows the expected yield reduction for several crops at various ECs. Use Table 4 to match the salinity level to crops considered suitable.

Plants are most susceptible to salinity at germination, becoming more salt-tolerant as they mature. Where germination is the primary concern, leaching all salts out of the root zone usually is not feasible or required. Moving salts away from the germinating seed is all that may be needed (Figure 4, page 11).

Soils can remain productive even where complete reclamation is not possible. These situations require careful management and continual monitoring to ensure that productivity remains acceptable. For example, highly saline waste water generated from a coal-fired power plant has been used for irrigation with a combination of adequate acreage, water applied in slight excess of evapotranspiration, and use of tolerant crops (such as alfalfa and barley).

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.

Since salts increase the osmotic potential of soil water, plants have greater difficulty absorbing water under saline conditions. Therefore, saline soil must be maintained at a higher moisture level than nonsaline soil for a crop to obtain adequate water. This often requires more frequent, but lower volume, irrigations. Drip irrigation can be effective in maintaining 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 kind and quantity of salts present. Remember, anything soluble in water will add to the salt load and increase soil EC.

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

Management of sodic soils

Sodic soils usually are the most expensive to reclaim and, 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 a sodicity problem must have drainage to facilitate sodium removal from the root zone. When a high water table is part of the problem, it must be lowered before reclamation can proceed. Drainage can also 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, but 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.

Watering and Hilling Strategies for Furrow-irrigated Crops with Different Soil Salt Concentrations

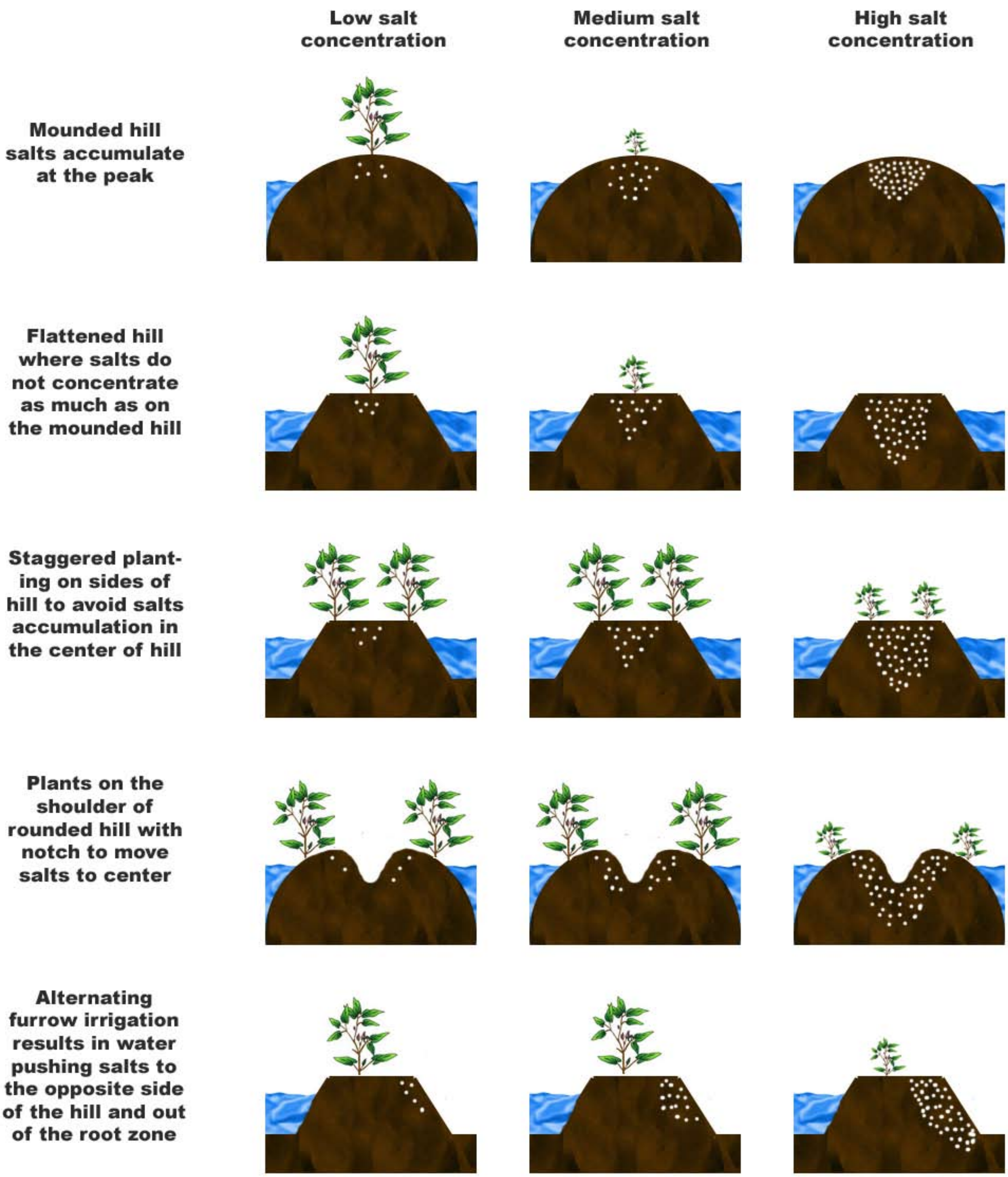

Figure 4.—Strategies for moving salts away from germinating seeds. Adapted with permission from Treating Irrigated Arid-Land Soils with Acid-Forming Sulphur Compounds*. 1979. Technical Bulletin 24. The Sulfur Institute.*

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 usually can tolerate higher ESPs (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.

Calcium is required for sodic soil reclamation, as it will displace sodium and reduce the ESP and SAR (Figures 5 and 6). If possible, use irrigation water that is high in calcium and salinity during the initial phase of reclamation. Injecting gypsum into irrigation water increases salinity and calcium. As the sodium is replaced, water lower in calcium and salinity can be used. Heavy applications of manure or old alfalfa hay worked into the soil will dissolve existing lime and release calcium as decomposition progresses.

Gypsum (calcium sulfate) is the most common material used to supply calcium for sodic soil reclamation. The "gypsum requirement"

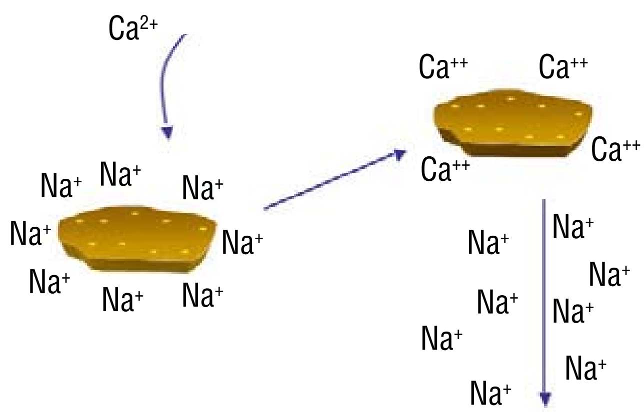

Figure 5.—Apply a source of calcium (such as gypsum) before leaching salts out of soils susceptible to dispersion. Replacing sodium with calcium before leaching will stabilize soil structure.

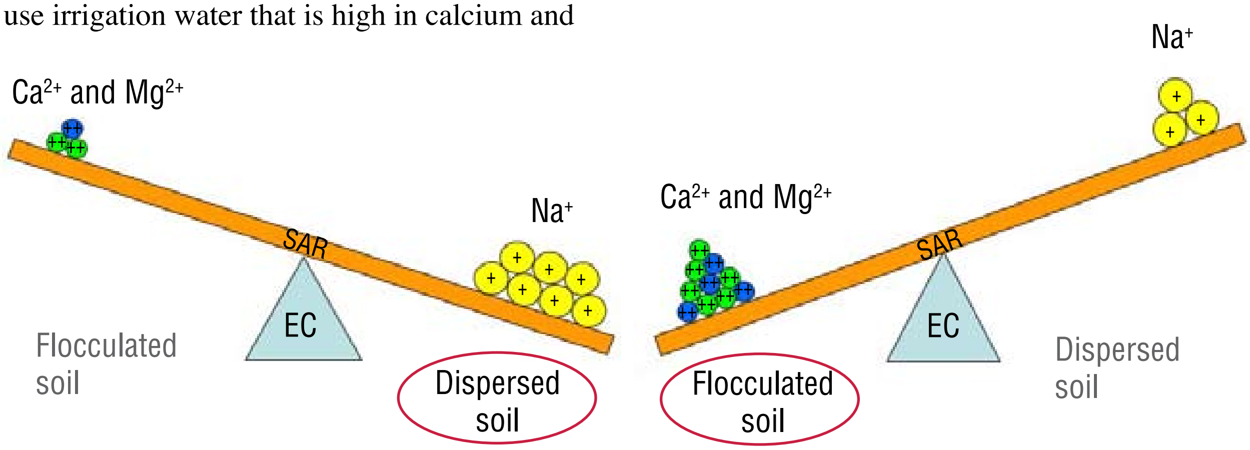

Figure 6.—The "teeter-totter" shows how soil structure (dispersed versus flocculated) depends on SAR (balance between Ca^{2+}, Mg^{2+}, and Na^+) and soluble salts (EC) in soil. Soil particles disperse (left) when (Ca^{2+} + Mg^{2+}) is decreased relative to Na^+ (SAR is increased). Soil particles flocculate (right) when (Ca^{2+} + Mg^{2+}) is increased relative to Na^+ (SAR is decreased).

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 considered a minimum. See “gypsum requirement” in the Glossary (page 19) for how to calculate the gypsum requirement for a specific soil. A soil test value for exchangeable sodium is needed to use Table 7.

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 greatly in excess of plant need.

Calcium nitrate or calcium chloride minerals can be used to reclaim sodic soils, but they generally are more costly and are likely to produce other negative effects on plant growth or the environment. Nitrate is considered a groundwater contaminant and is not a good choice.

Limestone is another commonly available mineral 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. Theoretically, limestone could be used if acidifying agents were also added to the soil. This solution is both impractical and expensive.

Elemental sulfur (S) can be used for sodic soil reclamation. Use elemental S only if 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, $CaCO_3$), 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 elemental S reactions in soil, see *Acidifying Soil for Crop Production: Inland Pacific Northwest,* PNW 599-E.

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, it is important to verify that the soil contains sufficient lime to dissolve.

Table 7. Amendment rates of gypsum and elemental sulfur (S) needed to reclaim sodic soils.

	Amendment rate			
Exchangeable Na to be replaced by Ca (meq Na/100 g soil)	**Gypsum (ton/acre) 12 inches**	**Gypsum (ton/acre) 6 inches**	**Elemental S[a] (ton/acre) 12 inches**	**Elemental S[a] (ton/acre) 6 inches**
1	1.8	0.9	0.32	0.16
2	3.4	1.7	0.64	0.32
4	6.9	3.4	1.28	0.64
8	13.7	6.9	2.56	1.28

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

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 equivalent to 1 ton of elemental S
Gypsum ($CaSO_4 \cdot 2H_2O$)	5.38
Lime-sulfur solution, 25% sulfur	4.17
Sulfur (soil must contain lime)[a]	1.00
Sulfuric acid (soil must contain lime)[a]	3.06
Iron sulfate ($FeSO_4 \cdot 7H_2O$) (soil must contain lime)[a]	8.69
Aluminum sulfate ($Al_2(SO_4)_3 \cdot 18\ H_2O$) (soil must contain lime)[a]	6.94

[a] 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 (see Figure 7).

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.*

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. Sodium must be made soluble in a saline-sodic soil before the soil is leached with clean (low-salt) irrigation water. If salts are leached with clean water while sodium is insoluble, the result may be a sodic soil. The resulting destruction of soil structure will prevent water infiltration. Once destroyed, soil structure is not easily corrected. Therefore, it is extremely important to know how much of

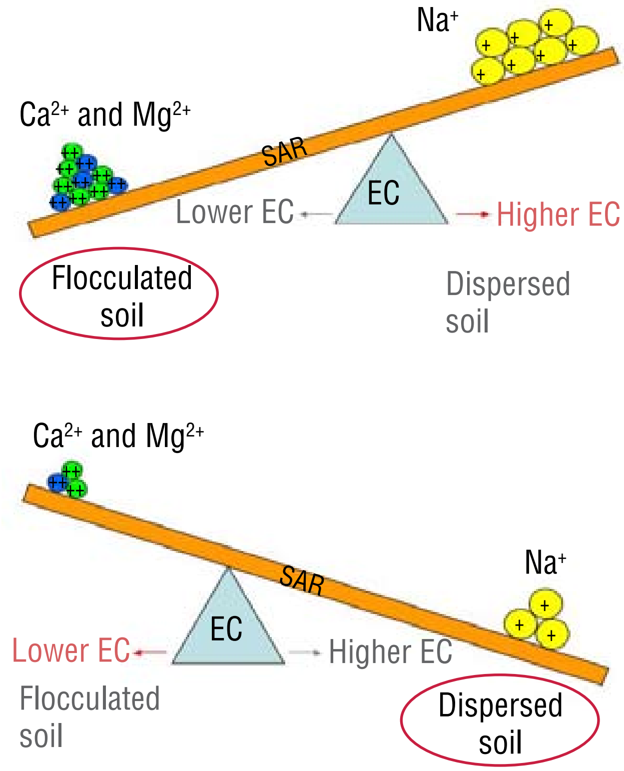

Figure 7.—Soil particles flocculate (top) when soluble salt in soil (EC) is increased, even when sodium is present. Soil particles may disperse (bottom) when soluble salt in soil (EC) is decreased, even when sodium is low.

a sodium problem exists before applying clean irrigation water to leach salts.

High EC irrigation water and soil helps maintain soil structure, increase water infiltration, and prevent sodium from dominating soil characteristics. 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 (e.g., pasture) to maintain soil cover.

Reclamation failures

When only part of a reclamation problem is considered, amending soils or leaching can make a situation worse. Consider the whole system. Drainage, pH, salts, and sodium are the main concerns. Examples of disasters to avoid include the following.

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.
Reduce pH (acidify) a noncalcareous soil. 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 clean (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 extremely slowly. Crop growth is reduced.

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

Soil testing questions and answers

What laboratory should I use? We recommend using a laboratory that uses standard methods for western soils (Table 2). Lists of laboratories are available as OSU Extension publication EM 8677 and WSU Extension publication EB 1578E (see "For more information," page 19).

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 percent, 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? Sodium adsorption ratio and exchangeable sodium percentage are both used to assess sodium problems, but they are not identical. Sodium adsorption ratio (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:

$$ESP = \frac{1.475 \times SAR}{1 + (0.0147 \times SAR)}$$

My laboratory reports in different units than those used in this publication. How do I convert units? Use Table 10 (page 18) to convert test values to other units. Analyses for pH, exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) are unitless and do not require conversion.

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

Component[a]	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	umhos/cm
Sodium, Na^+	ppm	0.00435	meq/100 g soil
Calcium, Ca^{2+}	ppm	0.0050	meq/100 g soil
Magnesium, Mg^{2+}	ppm	0.0083	meq/100 g soil
Sodium, Na^+	meq/100 g soil	230	ppm
Magnesium, Mg^{2+}	meq/100 g soil	120	ppm
Calcium, Ca^{2+}	meq/100 g soil	200	ppm
Cation exchange capacity (CEC), or exchangeable cation concentrations	meq/100 g soil	1.0	cmol (+)/kg

[a] 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 (cmole [+ 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:

$$ESP = \frac{Na^+, \text{ meq/100 g soil}}{\text{CEC, meq/100 g soil}} \times 100$$

To convert SAR to ESP, use the following equation:

$$ESP = \frac{1.475 \times SAR}{1 + (0.0147 \times SAR)}$$

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

Gypsum: $CaSO_4 \bullet 2H_2O$, 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 percent 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.

Osmotic potential: The water pressure exerted across a semipermeable membrane caused by an unequal concentration of salts or sugars on the two sides of the cell wall or membrane. Water will move from the side with the lower salt or sugar concentration through the membrane into the area with the higher salt or sugar concentration.

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. The pH is measured with a pH electrode and meter or dyes.

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:

$$SAR = \frac{[Na^+]}{\sqrt{0.5\,([Ca^{2+}] + [Mg^{2+}])}}$$

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

Management of irrigated soils

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Key concepts

- Salt accumulation in soil can reduce crop yields and irrigation effectiveness, ruin soil structure, and affect other soil properties.
- There are three types of salt-affected soils.

  Saline soils have salt (primarily calcium and magnesium). Salts in the root zone can make it difficult for plants to extract water from the soil.

  Sodic soils have sodium. High levels of sodium can cause soil particles to disperse, clogging soil pores and preventing water movement into and through the soil.

  S*aline-sodic* soils have problems with sodium *and* other salts.
- 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/or boron can reduce crop yield independent of saline and/or sodic soil conditions.
- Soil testing provides an indication of risk of soil and crop damage from salts.
- Reclamation of salt-affected soils requires adequate drainage. If necessary, improve drainage before attempting reclamation.
- *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 calcium to replace sodium in the soil solution. Calcium promotes clumping of soil particles, thus creating pore spaces and improving water movement.

  Gypsum is the most common material used to supply calcium for sodic soil reclamation.

  Elemental sulfur can be used for reclamation of sodic soils when free lime exists in the soil.

  Irrigation water can create or worsen sodic soil conditions, making irrigation water management important.
- *Saline-sodic* soils must be treated as sodic soils first. These soils require calcium to correct sodium. Once the sodium problem is corrected, leaching to remove salts is required.

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