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ALKALINE SOILS IN WYOMING

FORMATION, ECOLOGY, AND MANAGEMENT OF CALCAREOUS, SALINE, AND SODIC SOILS

INTRODUCTION

Alkaline soils occur where annual rainfall is less than about 20 inches per year, which includes most of Wyoming and the arid and semiarid West, as well as over 40 percent of Earth's land surface (Millennium Ecosystem Assessment, 2005). As defined for this bulletin, alkaline soils include calcareous, saline, sodic, and saline-sodic soils that are either naturally occurring or created by various disturbances. They underlie unique and fragile desert, grassland, and shrub-steppe ecosystems, as well as productive irrigated and dryland crops, but also pose management challenges that may require remediation practices to restore biodiversity and productivity.

Arid and semiarid ecosystems are fragile because plant growth often depends upon very thin topsoils, or A horizons, that are easy to disturb, difficult to restore, and overlay subsoils with higher concentrations of salts. Tillage, irrigation, erosion, heavy grazing, road building, energy

> Alkaline soils are characterized by soil-solution pH greater than 7.0, which is caused by buildup of water-soluble salts of calcium, magnesium, sodium, potassium, and other base-forming cations near the soil surface. The salts accumulate because there is not enough precipitation to move them deeper into the soil profile.

Table 1. Chemical characteristics of saline, sodic, saline-sodic, and calcareous soils. In Wyoming, saline, sodic, and saline-sodic soils are usually calcareous as well.

Classification	SAR	EC (dS/m)	Soil pH	ESP %	CaCO$_3$ content	Soil structure and porosity
Saline	<13	>4	<8.5	<15	Varies	Normal
Sodic	>13	<4	>8.5	>15	Varies	Poor
Saline-sodic	>13	>4	<8.5	>15	Varies	Normal or poor
Calcareous	Varies	Varies	>7.2	Varies	>0 (audible or visible effervescence)	Normal

Abbreviations: SAR, sodium adsorption ratio; EC, electrical conductivity of a saturated paste of soil; ESP, exchangeable sodium percentage. "Varies" means that this property is not diagnostic for a given classification. See text box "Identifying Important Properties of Alkaline Soils", below, for explanation.

IDENTIFYING IMPORTANT PROPERTIES OF ALKALINE SOILS

Several basic pieces of information indicate soil properties that limit production and may require remediation. While SAR and ESP require laboratory analyses, do-it-yourself observations of EC, pH, calcium carbonate (CaCO$_3$), and soil structure, along with some knowledge of the soil (see soil survey text box), are valuable. Calculating amendment rates, however, requires knowing the ESP from a soil lab.

Sodium Adsorption Ratio (SAR) is the proportion of Na relative to Ca and Mg in the soil solution. Concentrations of soil solution Na, Ca, and Mg from laboratory analyses are necessary.

Exchangeable Sodium Percentage (ESP) is the proportion of the cation exchange capacity (CEC) occupied by Na. Cation exchange capacity and exchangeable Na concentration from laboratory analyses are necessary.

Calcium carbonate content is determined in a lab or with a simple field test using dilute hydrochloric acid (or even vinegar). Described in the Calcareous soils section.

Electrical conductivity (EC) of the soil solution indicates the total dissolved solids, or salinity of the soil solution. This can be provided by a soil lab, but can also be measured in the field with relatively inexpensive hand-held meters made by several companies for around $100 and up. Beware that units of conductivity displayed on these meters can be confusing (see conversion chart on page 12).

pH of the soil solution indicates whether the soil is alkaline or acidic. It can be provided by a soil lab, but can also be measured in the field with pH meters, pH test kits, or pH paper strips. For test kits and paper strips, make sure that the range of pH measured extends to nine or above. Many are made for garden soils and might only extend up to pH 7.5.

To field test for soil solution EC and pH, first you must create a soil solution. Put about a tablespoon of soil and an equal amount of distilled water into a small plastic cup, then stir, or cap and shake, vigorously for about one minute. Insert the EC meter into the soil-water mixture until you can record a stable reading (the reading should stay the same for about 10 seconds). Then wait 10 to 15 minutes for the soil particles to settle and insert the pH electrode (or the pH paper) into the top of the solution. Record the pH reading when it stabilizes (within 30 seconds). Always measure EC first because the pH electrode can change the electrical conductivity. Be sure to properly calibrate, clean, and store the meters according to manufacturer's instructions.

Soil structure and porosity are easily observed indicators of sodicity. Intact naturally occurring sodic soils often have columnar structure in the shallow subsurface (B) horizon. Disturbed soils with sodic conditions at the surface may have durable crusts and lack the granular or blocky structure of healthy soils. They also lack porosity so are slowly permeable and water will pond rather than infiltrate the soil.

development, and other activities that disturb the soil surface or alter drainage or surface hydrology can increase surface salt concentrations.

High concentrations of potassium (K), calcium (Ca), and magnesium (Mg) salts can limit the ability of plants to take up water, while sodium (Na) salts cause soil aggregates to disintegrate, or disperse, plugging pores, forming hard crusts, and limiting water infiltration and movement. Identification and management of soils with high concentrations of soluble salts is important for maintenance and restoration of sustainable crop and forage production and wildlife habitat management in arid and semiarid regions. This bulletin covers the definitions, properties, assessment methods, effects on plant growth, and remediation strategies of alkaline soils, including calcareous, saline, sodic, and saline-sodic soils (Table 1).

CALCAREOUS SOILS

Calcareous soils contain measureable amounts of calcium carbonate ($CaCO_3$), also known as lime, caliche, or calcite. Calcareous soils occur in arid and semiarid regions with less than 20 inches of precipitation, and therefore occur almost everywhere in Wyoming except in the mountains. At higher precipitation, $CaCO_3$ is carried below the rooting zone. Calcium carbonate is not as soluble as other salts, so is relatively stable in the soil and does not accumulate at the surface during hot, evaporative weather, nor does it rapidly leach from the soil with heavy rain or irrigation.

The source of $CaCO_3$ may be parent materials originating from limestone or limestone alluvium, but it often forms in place as "pedogenic" $CaCO_3$. Formation of pedogenic $CaCO_3$ requires Ca (Ca^{+2}), which is supplied by mineral weathering and inputs with dust and precipitation. The Ca combines with carbonate (CO_3^{-2}) in the soil, which forms when carbon dioxide (CO_2) from plant and microbial respiration reacts with high-pH water. The formation of pedogenic $CaCO_3$ is a very slow process, but over time it can accumulate to high levels that, on stable surfaces over 1 million years old, can form rock-like, root-limiting petrocalcic horizons (Figure 1). Most calcareous soils are much younger and have a calcic horizon where $CaCO_3$ accumulates below the long-term leaching limit of water (the long-term average infiltration depth). This is called the Bk horizon and, in Wyoming, typically occurs within 6–12 inches

Figure 1. The surface of a petrocalcic horizon that occurs beneath shallow soils on 2-million year old, flat-topped terraces west of Laramie. With time in semiarid environments, accumulated $CaCO_3$ fills soil pores and solidifies into a rock-like soil horizon. This consolidated horizon can form an erosion-resistant layer and lead to development of table-mountain like landforms.

Figure 2. Fizz test.

of the soil surface. Soils that are strongly calcareous have visible filaments and concentrations of white $CaCO_3$.

A quick and easy field method for estimating $CaCO_3$ content, commonly known as the "fizz test", relies on placing a drop or two of dilute hydrochloric acid (HCl) on a soil sample and observing the reaction, or effervescence (Figure 2; Table 2). The concentration of dilute HCl should be approximately one Molar, or about one part concentrated HCl to nine parts distilled water (Soil Survey Division Staff, 2018). A slightly more complicated method uses common vinegar instead of dilute HCl (Zhu et al., 2015).

Calcium carbonate does not directly harm plant productivity unless it's present at extremely high levels that form root-limiting horizons. The supply of CO_3^{-2} reduces the activity of hydrogen (H^+) ions in the soil solution to keep soil pH in the alkaline range (about 7.2). Many calcareous soils in Wyoming have higher pH levels because of the presence of other salts. Plants that prefer acidic soils, such as blueberries, will not thrive in calcareous soils. The abundant Ca and the high pH can interfere with availability of phosphorus (P) by forming Ca-P minerals.

Phosphorus availability in calcareous soils is a big concern for Wyoming crop producers. The notion that the soil contains a great amount of P, and even adsorbs expensive fertilizers, is frustrating to farmers. A common question fielded by agronomists is "how can I reduce my pH to tap into my reserve of soil P?" Unfortunately, there is not an easy answer. The large amount of $CaCO_3$ in Wyoming agricultural soils makes acidifying the soil expensive and impractical. For example, elemental sulfur is commonly used to acidify soils because as it oxidizes to sulfate (SO_4^{-2}), reacting with water (H_2O) to release H^+ ions that decrease the pH. But to change the pH in calcareous soil, $CaCO_3$ must be solubilized. A soil containing just two percent $CaCO_3$ would require 6.4 tons of sulfur per acre (Havlin et al., 2011), at up to \$800 per ton. Even then the pH would stay alkaline because abundant basic cations on exchange in the soil would buffer the soil solution (would dissolve to replace H^+ in solution). As you will note if you start doing the fizz test around Wyoming, many soils have much greater than two percent $CaCO_3$ at or near the surface.

The better approach is to plant crops tolerant of somewhat alkaline conditions (pH ~ 8.0) and to carefully manage P and micronutrients by frequently testing the soil. In calcareous soils, P is usually available to the plant for a very short time compared with neutral or slightly acidic soils, so annual application is a good recommendation, rather than once per rotation, for instance. Banding P fertilizer is also a good approach because it places P where it is accessible to growing roots and creates less contact with the soil than broadcasting. Therefore, banding P slows down adsorption and fixation reactions.

Increasing soil organic matter content with organic amendments (compost) or conservation tillage creates organic acids as mineralization of organic material releases H^+, as does conversion of ammonium fertilizers to nitrate. But this does not produce enough acid to neutralize calcareous soils. However, management practices and amendments that increase surface soil organic matter content serve to dilute the effects of $CaCO_3$ and also improve soil water infiltration so that, over time, $CaCO_3$ can be moved below the surface, improving P and micronutrient availability during germination and establishment. Because of the low solubility of $CaCO_3$ relative to other salts, changes to soil pH and structure are slow and require long time commitments.

Table 2. Classification of carbonate reaction in the soil matrix.

Reaction with dilute hydrochloric acid (1M)	Description	Classification	Estimated percent $CaCO_3$
No bubbles detected	Noneffervescent	Non-calcareous	0
Audible effervescence	Very slightly effervescent	Slightly calcareous	0–2
Bubbles readily seen	Slightly effervescent	Moderately calcareous	2–10
Bubbles form low foam	Strongly effervescent	Strongly calcareous	10–25
Thick foam forms quickly	Violently effervescent	Extremely calcareous	>25

Food and Agriculture Organization, 2006

SALINE SOILS

Saline soils have an electrical conductivity (EC) in the soil solution greater than four decisiemens per meter (dS/m) and an exchangeable sodium percentage (ESP) of less than 15 (Table 1). Electrical conductivity is used to indicate salinity because the more ions are in solution, the more electricity water conducts. It is directly related to total dissolved solids (ppm TDS = 640 × EC), but EC is easier to measure.

Salts accumulate in regions where potential evapotranspiration exceeds precipitation. Salts released during mineral weathering, or added with irrigation water, fertilizer, or manure, are not leached from the soil profile. They may accumulate as white salt deposits during periods of soil water evaporation and were formerly called "white alkali".

Soluble salts contain the cations Na^+, K^+, Ca^{+2}, and Mg^{+2}, and the anions Cl, SO_4^{-2}, HCO_3-, and CO_3^{-2}. The main detrimental effects on plant growth are physiological drought and ion imbalances that cause the plant to require more energy. Physiological drought occurs when elevated salt concentration in the soil increases the tension with which water is held by soil particles and decreases its availability to plants. Chlorosis in older leaves and stunting are early signs of salt stress. Plants suffering salt stress have necrotic "burned" leaf margins. Conifer needles die from the tips back. This type of salt stress is common in potted house plants because dissolved salts in tap water, even at low concentration, accumulate unless the pot is occasionally overwatered to leach them out.

The tolerance of plants varies greatly by species. It pays for agricultural producers in saline conditions to select salt tolerant crops and to understand how soil EC affects yields of crops being grown. Table 3, page 6, gives the salt tolerance rating, the threshold soil EC, and the yield decrease per unit EC increase for some common Wyoming crops.

Management of saline soils requires two general strategies: reducing upward soil water movement by slowing evaporation at the surface, or increasing downward soil water movement (leaching). With rainfed or limited irrigation situations, organic mulches or crop residues on the soil surface, such as in reduced- or no-till management, reduce evaporation and increase water infiltration and leaching. Incorporating organic materials can serve to reduce salinity in surface soil due to

FINDING AND USING ONLINE SOILS INFORMATION

Soil Survey is the soil mapping effort of the USDA Natural Resources Conservation Service (NRCS). The soil survey provides information for broad-scale planning essential for basic understanding of a landscape. The mapping is large scale and provides reference-area information about the undisturbed condition, so understanding specific soil conditions for planning management and remediation requires on-site observations. The soil survey is now completely digital and accessible online in two ways.

Web Soil Survey (websoilsurvey.nrcs.usda. gov): This soil mapping program developed by NRCS provides access to the most current soil survey information, from raw laboratory data to interpretations of soil limitations for various land uses. The Web Soil Survey allows you to define an Area of Interest (AOI) of 100,000 acres or less on an aerial photograph and then explore soil properties within that area. You can create maps of soil EC, pH, and SAR, for example, as well as many other properties, land use suitabilities, and ecological sites. You can download GIS data, or create a custom soil survey report for your AOI.

SoilWeb Apps (casoilresource.lawr.ucdavis. edu/soilweb-apps) are convenient tools created by the Soil Resource Lab at the University of California, Davis in collaboration with NRCS. The online interface SoilWeb (casoilresource.lawr. ucdavis.edu/gmap/) is a seamless nationwide soil map that allows access to all the soil survey and ecological site information by just clicking on each map unit. The SoilWeb Earth App allows you to download a seamless soil layer for use in Google Earth. The SoilWeb iPhone App can be downloaded from the App Store. It uses your iPhone GPS to give you soil information for your current location (very cool! If you have cell coverage...).

both dilution and sorption of some salts, and also improve infiltration and leaching.

Leaching salts below the root zone is not difficult if abundant, low-salt irrigation water is available and soils are well drained. In contrast to sodic soils, saline soils usually have good drainage because salts are dominated by highly charged Ca^{+2} and Mg^{+2} ions that aggregate, or flocculate, soil particles, creating good soil structure and porosity, in contrast to the weakly charged Na^+, which tends to disperse soil particles, destroying soil structure and drainage (Figure 3).

The proportion of excess water required to leach salts is called the leaching requirement and can be calculated as follows:

$$\text{Leaching Requirement} = \frac{EC_{iw}}{5(EC_{target}) - EC_{iw}}$$

Where EC_{iw} is the EC of irrigation water and the EC_{target} is the target soil-solution EC. For example, if EC_{iw} = 1.5 dS/m and EC_{target} = 1 dS/m, the leaching requirement would be 0.43, or 43% more water than would saturate the soil.

To estimate the total amount of water required, we must know the *saturated soil water holding capacity* (WHC), which is the same as the amount of pore space in the soil, or soil porosity. Porosity is calculated from the bulk density of the soil as:

$$\text{Porosity (\%)} = 1 - \frac{bulk\ density}{2.65} \times 100$$

Where 2.65 g/cm³ is the estimated particle density of mineral soils (the density of quartz). Porosity ranges from around 35 percent for sandy soils to over 60 percent for clayey or organic matter rich soils. A good estimate for fine-textured soils with low organic matter content is 50 percent. At 50 percent porosity, each inch of soil would require about ½ inch of water to become saturated, plus additional water equal to the leaching requirement to remove salts. So each inch of soil to be leached would require:

$$\text{Total water required} = (\text{Depth to be leached}) \times (\text{saturated WHC}) \times (1 + \text{Leaching Requirement})$$

In the example above with EC_{iw} of 1.5, EC_{target} of 1, and leaching requirement of 0.43, to leach the top two feet of soil:

$$(24 \text{ inches} \times 0.5) \times (1 + 0.43) = 17.2 \text{ inches of water}$$

Table 3. Salt tolerance of selected crops (from Havlin et al., 2011). Information on more crops available via various Web sites (see reference section for some examples).

Crop	Threshold EC (dS/m)	% yield decrease per unit EC increase	EC at 50% yield loss	Salt tolerance rating[1]
Alfalfa	2.0	7.3	8.8	MS
Barley (forage)	6.0	7.1	13.1	MT
Barley (grain)	8.0	5.0	18.0	T
Bean	1.0	19	3.6	S
Bromegrass	2.5	7.2	8.7	MT
Clover (red, ladino, alsike)	1.5	12	5.7	MS
Corn (forage)	1.8	7.4	8.6	MS
Corn (grain, sweet)	1.7	12	5.9	MS
Orchardgrass	1.5	6.2	9.6	MT
Soybean	5.0	20	7.5	MT
Sugarbeet	7.0	5.9	15.5	T
Wheat	6.0	7.1	13.0	MT

1S, sensitive; MS, moderately sensitive; MT, moderately tolerant; T, tolerant.

For irrigated agriculture, the goal is often to leach salts below the crop root zone. For reclamation, there is sometimes limited water available, though it may be feasible to leach the surface two or three inches to facilitate germination of native, salt-tolerant plants. This essentially speeds up the natural process of removing salts from a shallow A horizon.

SODIC AND SALINE-SODIC SOILS

Sodic soils have an ESP greater than 15 percent and EC less than 4 dS/m, while saline-sodic soils have chemical characteristics of both: ESP greater than 15 percent and EC greater than 4 dS/m (Table 1). Sodic and saline-sodic soils occur naturally in landscape depressions in desert basins in Wyoming, especially those underlain by sodium-containing marine shale parent materials. Soil morphological descriptions denote a Bn, or natric horizon, often within two to six inches of the soil surface. Often, the natric horizon co-occurs with a calcic and clay-enriched horizon, a Btkn horizon. The thin A horizon over the natric horizon is very important for plant germination and establishment and is easily destroyed by erosion or during development activities.

Sodium is especially problematic because, with its monovalent (+1) charge, large hydrated ionic radius (size), and low charge density due in part to a tendency to attract water molecules as a "water jacket," it disperses soil particles, forcing them apart and destroying soil structure and water movement (Figure 3). Sodic conditions are also toxic to plants because Na can replace Ca in cell membranes, increasing permeability and loss of ions. Sodium accumulation causes leaf-edge necrosis, especially in grasses. Large amounts of Na also overwhelm the pH buffering effects of $CaCO_3$, so that pH can increase to nine or higher, causing micronutrient deficiencies. Soils with high contents of shrink-swell clays, also common in Wyoming, are especially prone to problems and may become almost impervious to water, forming "slick spots" on the soil surface.

Management of Na in the soil requires reducing the ratio of Na to the other cations (K, Ca, and Mg). That's why it is
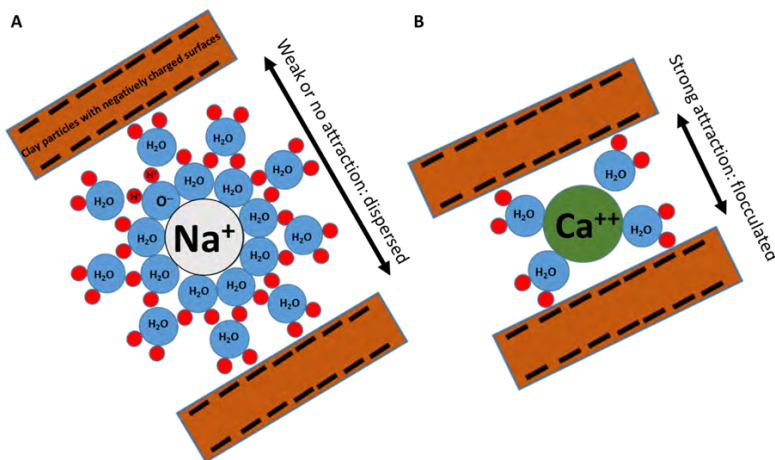

Figure 3. Simplified schematic diagrams of (A) a dispersed soil in which the thick shell of water molecules of strongly hydrated Na ions force negatively charged soil particles apart, destroying soil aggregates and reducing porosity as individual particles plug pores, and (B) a flocculated soil in which less strongly hydrated Ca ions are closer to clay surfaces, forming a strong attraction and binding aggregates together to form inter-aggregate porosity. Larger silt and sand particles could also be bound within aggregates formed by the flocculated clay particles. Mg and K ions have intermediate hydration strength, so flocculate particles less strongly than Ca.

**RECLAMATION EXAMPLE:
LEACHING THE GERMINATION ZONE**

EC_{iw} = 2 dS/m: local well water available for limited irrigation from a water truck;

EC_{target} = 4 dS/m for establishment of native salt-tolerant plants;

Leaching Requirement =

$$\frac{EC_{iw}}{5(EC_{target}) - EC_{iw}}$$

$$\frac{2}{5(4) - 2}$$

$$=0.11$$

Depth to leach = 3 inches

Saturated WHC = ~50%, or 0.5

(3 inches x 0.5) × (1+0.11)=1.67 inches

Covering one acre, at 27,150 gallons per acre inch (see conversion table) would require 45,340 gallons. Water tank trucks typically hold 3000 to 10,000 gallons. Keep in mind that the water intake rate for fine-textured soils is about 0.1 to 0.3 inch per hour, so sprinklers should be set up to avoid runoff and erosion.

measured as ESP or sodium adsorption ratio (SAR). These two measurements are related, but ESP is derived from the cations on exchange, or held on negatively charged surfaces of clay and SOM particles and requires extraction of Na, Ca, and Mg using an extractant that displaces the ions on the cation exchange. ESP is calculated as:

$$ESP \quad = \quad \frac{\text{Exchangeable Na}}{\text{CEC}} \times 100$$

Where units of exchangeable Na and CEC are meq/100g soil. SAR is derived from cations in the soil solution and not held on exchange surfaces, so extractable with water. SAR is calculated as follows:

$$SAR \quad = \quad \frac{\text{soil solution Na}}{\sqrt{\dfrac{\text{solution Ca+Mg}}{2}}}$$

Where all units are meq/L.

The ESP value is needed to estimate the rates of amendments necessary to displace exchangeable sodium in order to remediate sodic or saline-sodic soils. Both the solution and exchangeable concentrations are needed to calculate ESP because the extraction process for exchangeable ions also extracts the solution ions, so exchangeable = total extractable – solution. But the exchangeable and solution concentrations are closely related, so ESP can be estimated from SAR if only solution concentrations are available. In cases where only the SAR is available, ESP can be calculated as follows:
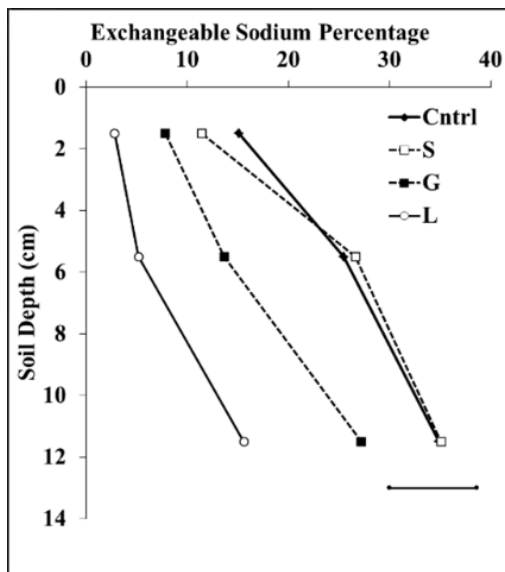
$$ESP \quad = \quad \frac{1.5 \, SAR}{1+(0.015 \, SAR)}$$

There are several chemical amendments that can be used to displace Na on the cation exchange with Ca or Mg, including gypsum ($CaSO_4 \cdot 2H_2O$) and langbeinite ($MgKSO_4$). This reduces the ESP and improves soil structure so that salts can then be leached. The problem is that most of our saline soils are also calcareous. By adding more salts, salinity (EC) can be increased to harmful levels, but usually temporarily.

In calcareous soils, most Ca is present as $CaCO_3$ so, in theory, by acidifying the soil it should release Ca that will displace Na on exchange so that Na can be leached and sodic conditions alleviated. In practice, however, the high concentrations of Na in saline-sodic soils means that large amounts of acid are needed. Elemental S can be used because it forms sulfuric acid as it oxidizes in the soil, but adding enough to reduce sodicity is usually cost prohibitive, and the effect is temporary.

University of Wyoming Extension bulletin B-1231, *Reclamation on Salt/Sodium-affected Soils* (Norton and Strom, 2012), discusses options for reclaiming soils drastically disturbed by development activities. Such activities often move Na and other salts to the soil surface where they cause crusting and salinity that makes establishment of desirable plant communities very difficult. In recent research, we evaluated the effects of chemical amendments and compost in reclamation of soils that became saline-sodic during the development and reclamation process. We found that langbeinite can mobilize and reduce the amount of Na in the soil (Figure 4), improving soil structure and drainage, but temporarily increasing EC to levels that may be unacceptable. Gypsum, elemental S, and compost were not as effective at alleviating saline-sodic conditions in the short term. Since the reactions required for these amendments to be effective require water, they may require more time.

Figure 4. ESP at three depths with four amendments one year after application. Initial ESP was 38.6 at all depths. Cntrl, untreated control; S, elemental sulfur; G, gypsum; L, langbeinite. Horizontal line represents least significant difference.

CALCULATING RATES OF CHEMICAL AMENDMENTS

Chemical amendments replace bad-guy Na^+ ions held on the soil cation exchange with good-guy Ca^{+2}, Mg^{+2}, or K^+ ions. So determining amendment rates requires knowing how much excess Na^+ is taking up space in the cation exchange capacity of the soil. There are several sources of the good guys:

- Gypsum ($CaSO_4 \cdot 2H_2O$) is a source of extra Ca^{+2} ions and is a common amendment for sodium-affected soils;

- Langbeinite ($K_2Mg_2(SO_4)_3$) is a source of K^+ and Mg^{+2} ions is more soluble and faster-acting than gypsum but can temporarily raise salinity levels;

- Elemental sulfur (S) can release Ca^{+2} ions from soil $CaCO_3$.

With elemental S, soil microbes oxidize S to form sulfuric acid, which dissolves some $CaCO_3$ and releases Ca^{+2} ions. Microbial processes require moisture, soil organic matter, and warm temperatures. Degraded soils in Wyoming are short on all three, so remediation with elemental S can be a slow process.

Whatever the source of good-guy ions, the amendment application rate is calculated on a charge-per-charge basis because each Na^+ ion occupies one negative charge on the cation exchange. So, each Ca^{+2} or Mg^{+2} ion displaces two Na^+ ions, while each K^+ ion displaces one Na^+ ion. Once the required number of ions is known, then the molecular weight of the amendment is used to determine the application rate in pounds per acre.

In order to calculate amendment rates, a minimum of the following information is required:

- **Cation ion exchange capacity** (CEC), expressed as the number of charges per 100 grams of soil (milliequivalents -meq- per 100g soil);

- **Exchangeable Na concentration**, used to calculate the exchangeable sodium percentage (ESP), or the percentage of the CEC occupied by Na;

- **The desired ESP** (usually 15 or less to improve porosity and drainage); and

- **Presence of CaCO₃** (can be determined with fizz test, and any amount more than zero will do).

Step 1: Determine amount of Na^+ in excess of the desired ESP. This is the amount that needs to be removed from the cation exchange, in meq Na^+/100 g soil.

$$\frac{measured\ ESP - desired\ ESP}{100} \times \frac{CEC\ meq}{100g\ soil} = \frac{meq\ Na\ to\ be\ displaced}{100g\ soil}$$

Step 2: Determine presence of $CaCO_3$. If $CaCO_3$ is present (the soil fizzes with dilute HCl), then elemental S can be used to slightly acidify the soil and release Ca to displace Na on the cation exchange.

From here, the graphs shown in Figure 5 can be used to determine amendment rates, or they can be calculated using Step 3.

Step 3: Determine quantity of S, gypsum, or langbeinite needed. In this step, the molecular weight of each element and amendment is used to determine how much one meq of each weighs and then to convert to grams per 100 g soil and to pounds of amendment per acre to treat the top six inches of soil (Havlin et al., 2014).

Using a shortcut, each meq Na$^+$/100 g soil to be removed (calculated in step 1) requires:

- 1720 lbs gypsum/acre

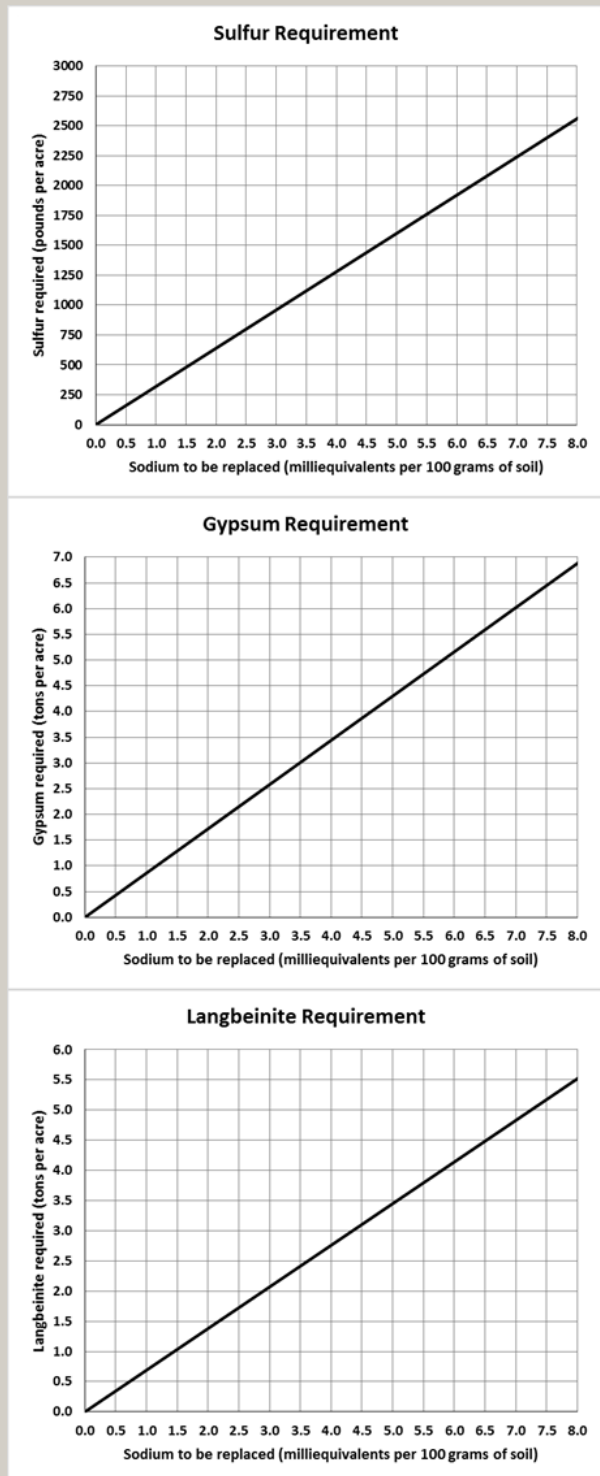- 320 lbs S/acre

- 1380 lbs langbeinite/acre

Figure 5. Graphs for determining application rates of selected amendments. Determine amount of sodium to be replaced using lab data and Step 1 (previous page), then find the sodium to be replaced on the horizontal axis of the correct graph and use the linear relationship to determine the rate on the vertical axis.

DEFINITIONS

anion   Elemental ion with a negative charge.

cation   Elemental ion with a positive charge.

cation exchange   Base cations (mainly Ca, Mg, K, and Na) that can be held electrostatically on negatively charged clay and organic matter particles.

CEC   Cation Exchange Capacity. Amount of base cations that can be held electrostatically on negatively charged clay and organic matter particles, expressed in meq/100 g soil

Dispersion   Generally undesirable process in which excess weakly charged sodium ions (low charge per ionic radius, or charge density) force soil particles apart, destroying aggregates, plugging soil pores, forming dense crusts, and impeding soil water infiltration and movement.

ESP   Exchangeable Sodium Percentage. Exchangeable sodium divided by the cation exchange capacity times 100.

Exchangeable ions Ions held on cation exchange, extractable with potassium chloride, ammonium acetate, and other extractants that provide cations to displace those on exchange. These extractants remove both exchangeable and solution (water extractable) ions, so: exchangeable = extractable – solution.

Flocculation   Generally desirable process in which soil particles adhere to one another to form aggregates that increase porosity and water holding, infiltration, and movement. Flocculation is facilitated by organic matter and strongly charged cations, including Ca, Mg, and K (relatively high charge per ionic radius, or charge density), which adhere to negatively charged particle surfaces to hold them together.

pH   Negative log of $[H^+]$, which indicates the acidity (pH < 7) or alkalinity (pH > 7) of a soil.

SAR   Sodium adsorption ratio. Soil solution sodium concentration divided by one-half the square root of Ca plus Mg concentrations when expressed in meq/L.

soil solution   Soil water and dissolved ions. Ions extractable with water.

SOME COMMON CONVERSION FACTORS

Measurement	To convert	Multiply by	To obtain
Area	Hectare, ha	2.47	Acre, ac
Rate or yield	Kg/ha	0.893	Pounds/ac (about the same)
Rate or yield	Mg or tonne/ha	0.446	Ton/ac (about half)
Liquid nutrient concentration	mg/L	1	ppm
Soil nutrient concentration	mg/kg or µg/g	1	ppm
Electrical conductivity (EC of water)	EC, dS/m	1	Total dissolved solids (TDS), mg/L
EC	dS/m	1	mmhos/cm
EC	mmhos/cm	1000	µmhos/cm
EC	dS/m	100	µS/cm
EC	S/m	10	dS/m
Water application	Acre-inch	27,150	Gallons
Exchangable nutrient concentration or CEC	meq/100 g soil	1	cmolc/kg soil
Amendment application	meq/100 g soil	20	Pounds/acre
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

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