ATTRA Sustainable Agriculture

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Saline and Sodic Soils: Identification, Mitigation, and Management Considerations

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Contents

Excess salts in the ground pose a far-reaching and expanding threat to agriculture across the globe. This publication discusses how salinity affects plant growth, yield, and soil structure. It explains how soil salinity is measured and presents innovative strategies for preventing and mitigating soil salinity through management and addition of organic material.

Salty irrigated soil planted with 12 species of cover crop. Only stunted mustards and weeds emerged. This soil has an EC of around 13. Photo: Rex Dufour, NCAT

Introduction

The presence of excess salts in the ground is a far-reaching and expanding threat to agriculture across the globe. Increases in soil salinity are considered to be the primary stress to global crop production (Laidero, 2012). According to the Food and Agriculture Organization of the United Nations, 1% to 2% of all irrigated acreage is taken out of production every year due to excessive salt loads. Addressing these issues before it is too late has become imperative to maintaining the continued productivity of certain regions.

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Cadillac Desert, by Marc Reisner (1993), provides a warning to all who plough forward untempered into the American desert:

> Desert, semidesert, call it what you will. The point is that despite heroic efforts and many billions of dollars, all we have managed to do in the arid west is turn a Missouri-size section green – and that conversion has been wrought mainly with nonrenewable groundwater. But a goal of many … has long been to double, triple, quadruple the amount of desert that has been civilized and farmed, and now these same people say that the future of a hungry world depends on it, even if it means importing water from as far away as Alaska. What they seem not to understand is how difficult it will be just to hang on to the beachhead they have made. Such a surfeit of ambition stems, of course, from the remarkable record of success we have had in reclaiming the American desert. But the same could have been said about any number of desert civilizations throughout history – Assyria, Carthage, Mesopotamia; the Inca, the Aztec, the Hohokam – before they collapsed.
>
> And it may not have even been drought that did them in. It may have been salt.

The destruction of arable land has had some profound and lasting social and economic effects. In their *Assessment Report on Land Degradation and Restoration,* the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Service (IPBES) says that 190 million acres of primarily irrigated land have been permanently lost to salinity. Furthermore, there are currently 150 million acres of arable land damaged by salinization (Montanarella et al., 2018). Within the United States, the most affected areas are located in the arid western portion of the country. The Colorado River Basin, which includes parts of California, Colorado, Arizona, Nevada, New Mexico, Utah, and Wyoming, has seen particularly concentrated effects (LaHue, 2017).

Arid and *semi-arid* environments are most at risk, due to a dependence on irrigation water that tends to contain higher levels of salt. Once on the surface, the water evaporates, leaving salts behind. Notice the correlation between arid regions of the world and the distribution of saline, sodic, and saline-sodic soils in Figure 1. Irrigation on arid lands naturally produces areas of high salt concentration unless these salts are leached out by rainfall or the application of "clean" irrigation water. However, in these climates, rainfall is generally not sufficient to leach salts deeper (away from the root zone) into the soil profile. Without intervention and careful, ongoing management, soils currently affected by the buildup of salts will continue to store more and more salts in the upper layers of the soil profile, where plant germination and growth can be affected. It doesn't take many years for salt deposits to build up to levels that are toxic to many species of plants.

Soils and plants impacted by excess salts can exhibit detrimental effects on their physical, chemical, and biological properties. Land-use options and productivity are adversely affected by excess salts, which can lead to a drop in land value. Depending on the amount and type of salt in the soil, impacts will differ (McCauley and Jones, 2005). In this publication, we will explore the types of salts and their associated challenges in greater detail. Additionally, we will explore the testing and remediation of soils with excess salts.

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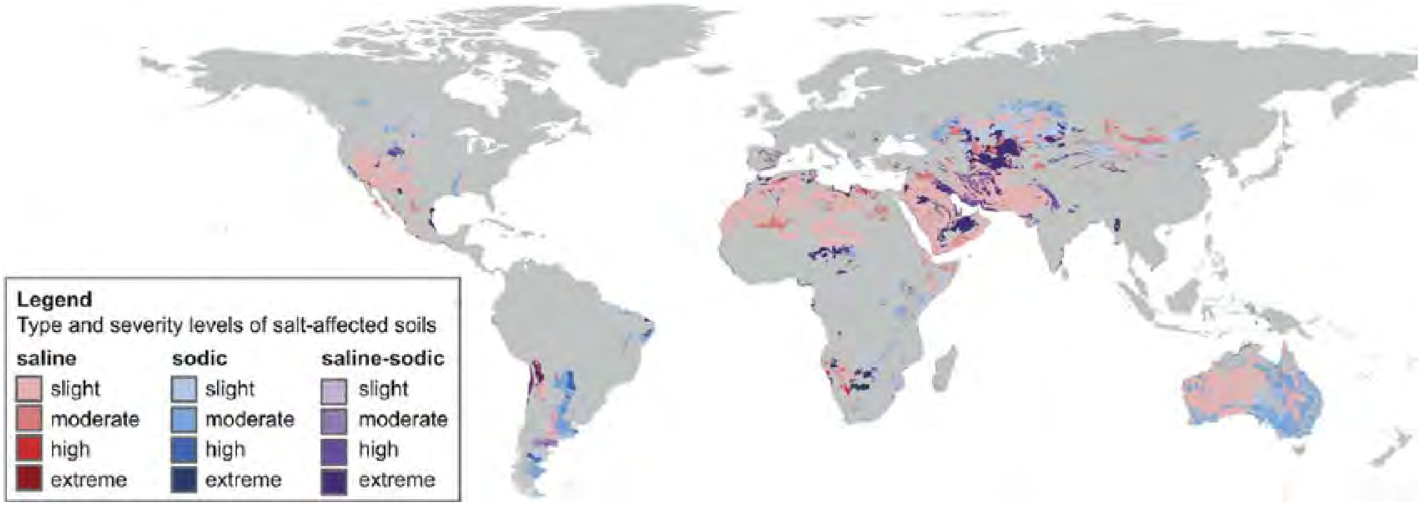
Figure 1. Type and Severity Levels of Salt-Affected Soils



Source: Wicke et al., 2011

Sources and Causes

The vast majority of salts come from the natural weathering of parent material, which includes minerals from bedrock and ancient sea beds (Cardon et al., 2007). Water-soluble salts are flushed from the parent material and flow downward into subterranean water basins, which are a primary source of irrigation water. Other sources of salts include damming of rivers, excessive use of agricultural fertilizers, municipal runoff, and water treatment with "softeners." In coastal areas, excessive pumping of groundwater can create intrusion zones where salty sea water penetrates into freshwater aquifers. Sea water intrusion of groundwater pumping sites occurs most prominently when there is insufficient groundwater recharge from rain and rivers to offset the amount being pumped out.

Arid and semi-arid regions are characterized in part by their limited annual precipitation. During dry periods, groundwater recharge slows and pumping increases. These combined factors cause groundwater levels to drop and salt deposition on the soil surface to increase. Droughts in these regions exacerbate the issue. To take an example from the Central Valley of California, "…salt in the San Joaquin Valley continues to increase, especially during drought years. That's because, during droughts, California's farms and cities rely on groundwater for up to 60 percent of their freshwater supply, up from 35 percent in non-drought years, and groundwater tends to be saltier than river water. People have been using groundwater faster than it naturally replenishes, dropping water levels deeper underground" (Gies, 2017).

Salinity Effects on Plant Growth and Yield

Stress in the form of salinity is the most limiting environmental factor affecting plant growth in regions where rainfall is limited (Parida and Das, 2005). Salts limit plant growth via several pathways. First, saline soils reduce a plant's ability to absorb water. "Osmotic stress symptoms are very similar to those of drought stress, and include stunted growth, poor germination, leaf burn, wilting and possibly death" (McCauley and Jones, 2005). These symptoms, similar to drought stress, occur even when water is present in the soil. In addition to affecting a plant's ability to take up water, excess salinity can affect nutrient availability and uptake, and it can cause toxicity issues from sodium and chlorine (Evelin et al., 2009).

Well aggregated soil allows for efficient water infiltration, providing better opportunity to leach salts to below root levels. Photo: Rex Dufour, NCAT

Surface crusting as a result of poor soil structure. The crust prevents water and air infiltration into the soil. Photo: Rex Dufour, NCAT

The effects that salt have on plants vary depending on the type of crop being grown, the amount of salt, and the type of salts in the soil. The presence of salts in the shallow layers of the soil profile will have a greater negative impact than those at layers further down in the profile, due to their proximity to plant roots.

Salt tolerance varies greatly from crop to crop. Carrots and strawberries, for example, are sensitive enough to suffer yield and growth losses in soils considered to be "very slightly saline," while asparagus and chard are tolerant to much higher levels of salts. Each crop species has a corresponding level of tolerance to salinity and, beyond this level, growth and yield begin to diminish (see Table 1 for more information on crop-specific tolerance levels). Many plants will not display negative effects of salinity stress; thus, observational analysis may not be sufficient to determine if salts are affecting the yield of a particular crop. Salt stress can darken leaves and restrict growth, but plants may otherwise appear healthy (Maas and Grattan, 1999).

Salinity and the Soil

Salinity and *sodicity* are the two salt-related problems that impact land managers around the globe. They are similar in many of their characteristics but should be managed differently due to the chemical differences in their composition. *Saline-sodic* soil is the third possibility. These soils exhibit traits of both types and require a management approach similar to that for sodic soils.

The most common salts include sodium (Na^+), magnesium (Mg^{2+}), and calcium (Ca^{2+}); other salts present, but to a lesser extent, include potassium (K^+), chloride (Cl^-), bicgarbonate (HCO_3^-), and sulfate (SO_4^{2-}).

Soil structure is one of the fundamental aspects of a soil that can help us understand whether it is functioning properly. Soils are composed of varying proportions of sand, silt, and clay. Structure relates to the way these particles aggregate, or clump together, on a chemical level. Well aggregated soils allow for healthy soil function, which includes the soil's ability to circulate air and percolate water down into the profile. Changes observed in soil structure or function may indicate salinity issues.

Soils characterized as saline or saline-sodic can be a wolf in sheep's clothing because they can appear to have good structure while negatively impacting other biological and chemical properties. Sodicity, on the other hand, is a specific salinity issue, in which too much sodium (Na) can further complicate the plant-soil relationship through the breakdown of soil aggregates. Sodic soils will facilitate the development of surface crusts, which hamper the germination and emergence of seedlings. These crusts form dense layers that inhibit root growth and make tillage more difficult. The destruction of soil aggregates also reduces pore structure and causes a settling of soil particles that are loosely or not at all associated to their neighboring particles (Abrol et al., 1988).

The physical structure of sodic soils, as described above, also leads to topsoil that is highly susceptible to the erosive forces of wind and water.

Another distinguishing characteristic of sodic soils is that they have a high pH, usually 8.5 or higher. On its own, high pH tends not to adversely affect most plants negatively. It is the tendency of high pH soils to decrease the availability of essential nutrients, including calcium, magnesium, phosphorus, potassium, iron, manganese, and zinc, that is cause for concern. All these minerals are also used by soil microbes, some of which have roles as mediators between the plant and the soil in process of accessing these minerals.

Table 1. The Effect of Electrical Conductivity on Plant Yield

	% Yield						**% Yield**				
Crops/ plants	**100%**	**90 %**	**75%**	**50%**	**0%**	**Crops/ plants**	**100%**	**90%**	**75%**	**50%**	**0%**
Barley	8.0	10.0	13.0	18.0	28.0	Radish	1.2	2.0	3.1	5.0	9.0
Sesbania	2.3	3.7	5.9	9.4	17.0	Spinach	2.0		5.3	8.6	15.0
Sorghum	4.0	5.1	7.2	11.0	18.0	Sweet corn	1.7		3.8	5.9	10.0
Wheat	6.0	7.4	9.5	13.0	20.0	Sweet potato	1.5	2.4	3.8	6.0	11.0
Beans	1.0	1.5	2.3	3.6	7.0	Tomato		3.5	5.0	7.6	13.0
Cabbage	1.8	2.8	4.4	7.0	12.0	Alfalfa	2.0	3.4	5.4	8.8	16.0
Sweet melon	2.2	3.6	5.7	9.1	16.0	Wheat grass	7.5		1 1.0	15.0	22.0
Carrot	1.0	1.7	1.7	4.6	8.0	Almonds	1.5	2.0	2.8		7.0
Cucumber	2.5	3.3	4.4	6.3	10.0	Date palm	4.0	68	10.9	17.9	32.0
Lettuce	1.3	2.1	3.2	5.2	9.0	Pomegranate					
Pepper	1.5	2.2	3.3	5.1	9.0	Lemon	1.7	2.3	3.3		8.0
Potato	1.7	2.5	3.8	5.9	10.0	Orange	1.7	23	3.3	4.8	8.0

Source: Ayers and Westcot, 1985. Top row of numbers represent % of potential yield. Numbers in table represent soil EC (measured using saturated paste method).

Example: Sweet potato grown in soil where ECe measures 3.8 can be expected to yield around 75% of maximum.

Note: These numbers represent rough guidelines that will be influenced by a number of factors, including cultivar chosen, soil temperature, cultural practices, and use of rootstocks, to name a few.

Table 2. Some Characteristics of Saline and Sodic Soils
Source: Adapted from Deneke, 2011

Soil Salinity Classification	EC	SAR	pH	Soil Condition
Saline	>4	<13	<8.5	Aggregated
Sodic	<4	>13	>8.5	Disperse
Saline-Sodic	>4	>13	<8.5	Aggregated

Test Results: Looking at EC and SAR

Three factors that are typically examined in order to determine a soils classification in terms of salinity are Electrical Conductivity (EC), Sodium Absorption Ratio (SAR), and pH (potential hydrogen).

Electrical Conductivity (EC), sometimes referred to as *specific conductance,* measures the ease with which current can pass through an object; in this case the object is the soil (ECe) or irrigation water (ECw). The more salt in a sample, the more easily a current will pass through that sample. Lab test results will provide measurements in the form of millimhos per cm (mmhos/cm) or decisiemens per meter (dS/m). These units are equivalent to one another: 1 mmoh/cm = 1 dS/m.

Sodic soils are distinguished by having higher concentrations of sodium (Na^+) relative to calcium (Ca^{2+}) and magnesium (Mg^{2+}). The most reliable test for sodicity of soil or water is the *sodium absorption ratio* (SAR), which compares the concentration of sodium to calcium and magnesium. An alternate test that is also used to determine sodicity is the *exchangeable sodium percentage* (ESP). This test compares the amount of sodium relative to the *cation exchange capacity* (CEC) of the soil sample. CEC is a term that describes the ability of a soil particle (negatively charged) to bind to positively charged molecules or elements like salt (Hazelton and Murphy, 2016). When sodium binds to a soil particle, it can only form one connection. The resulting particle then repels neighboring particles, leading to soil that is dispersed, with poor structure and limited water-holding capacity.

Testing Soil for Salinity

When conducting tests for salinity, it is valuable to take multiple samples at varying depths in order to measure two important factors: 1) a benchmark for each of the soil layers measured (take note of the relative distribution of salts at each layer); and 2) the degree to which salts are being flushed deeper into the soil profile over time, as management and prevention measures are being implemented. A good starting point is to sample to a depth of two feet in increments of six inches. Testing in this manner will allow the farmer to make note of whether salts present

Table 3. EC and Salinity Classification of Soils
Source: Scianna, 2002. www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044788.pdf

Salinity Class	EC (electrical conductivity) dS m^{-1} or mmhos cm^{-1}
Nonsaline	0-2
Very slightly saline	2-4
Slightly saline	4-8
Moderately saline	8-16
Strongly saline	>16

in the soil profile are working their way deeper and out of reach of plant roots. The grower should request the soil lab's analysis and recommendations for addressing the soil's salt/sodium issues. And these recommendations should be, well, taken with a grain of salt. If possible, get a second opinion.

Water Testing for Salinity

Testing irrigation water is just as important as testing the soil. In farm settings, irrigation water and shallow saline water tables are the primary means through which water-soluble salts make it to the soil surface (Maas and Grattan, 1999). It is useful to note the relative impact the water may have on the soil, based on its concentration of salts. Table 4 can be used to estimate the potential impacts that irrigation water will have on plants, as well as its potential to deposit excess salts.

Table 4. Measurements of Salinity for Irrigation Water
Source: Adapted from Fourie, 2017

Quality of Irrigation Water	EC dS/m mmhos/cm	SAR	Risk of Sodicity from Irrigation Water
Excellent	0-.80	1-10	Low
Good	.80-2.5	10-18	Moderate
Saline*	2.5-5	18-26	High
Very salty*	>5	>26	Very high

**Leaching may be necessary, and good management practices that promote soil health are recommended.*

Considerations for Testing Water
Due to the natural ebb and flow of salt concentrations with the seasons, irrigation water and soil tests will tend to correlate with higher concentrations during dry periods and lower concentrations during the rainy season. Take note of salt loads throughout the year.

- If you suspect or know that your farm is affected by salts, it may be beneficial to invest in an EC meter. Depending on the model, you will be able to test the soil, water, or both.
- Where is the sample taken? Irrigation radius (drip, sprinkler, micros) or between tree rows; bed or furrow; elevation within field (lower points tend to accumulate more salts).
- In general, a SAR test isn't a part of standard soil-testing parameters and needs to be ordered separately.

Prevention, Mitigation, and Management

Remediating Saline Soils

Aside from a few very expensive management options, flushing salts further down into the soil profile with clean (low-salt) water is the only way to directly lower salt concentrations in managed soils. Limiting the use of inputs that have high concentrations of salt, such as saline irrigation water, chemical fertilizers, or dairy manure, will serve as a good first step in reducing salt loads. Because good drainage is important to the leaching of salts, employing soil-management practices that improve soil structure and hydraulic flow through your farm's soil will aid in moving salts away from sensitive crop-growing areas.

Remediating Sodic and Saline-Sodic Soils

Due to low permeability, soils classified as saline-sodic or sodic require an additional step in order to effectively flush salts down into the soil profile, while maintaining or improving soil function. Some form of calcium, usually gypsum, is used to replace excess sodium present in the soil. Due to its stronger charge, calcium can replace the sodium attached to soil particles. Freed sodium then converts to salt in the form of Na_2SO_4, which is more easily leached from the soil. Some organic amendments have been shown to be excellent options when remediating alkaline soils (sodic soils tend to be alkaline).

Whether biochar, biosolids compost, or green waste compost is applied, each will reduce EC, ESP, and SAR to varying degrees, and when combined with gypsum, will reduce salinity to a greater degree than gypsum or organic components alone (Chaganti et al., 2015).

Management Practices for Soil Remediation

Particular management practices and related factors can increase the likelihood that salts will deposit on the soil surface. Poor management of irrigation water and excess tillage can exacerbate salinity problems. Excessive tillage, for example, can create a hardpan under the soil surface. This is a layer through which water percolates very slowly or not at all. Also, saline water sitting just below the soil surface can rise to the surface through capillary action. Capillary action describes the ability of water to move through narrow spaces regardless of external forces, including gravity. If you have ever left a paper towel to soak up water and watched the water spread across its fibers, you were observing capillary action. This is the same process that occurs in the soil when water is able to migrate upward through the soil profile. In this case, the water, with its load of salt, migrates to the surface, and the water evaporates continually, leaving ever-increasing amounts of salt behind.

The above-listed remediation techniques will do little to improve soil salinity conditions when hardpan layers or excessive soil compaction are present on the farm. In these situations, it may be advisable to break up impermeable layers mechanically ("ripping" the soil with deep ploughing or subsoiler), followed by a reduction in soil management practices that create these adverse conditions (Abrol et al., 1988). The reduction in salinity-enhancing management practices must be accompanied by implementation of practices that can help mitigate saline conditions, described in detail below.

Mitigating Saline Conditions: Addition of Organic Material

Adding organic amendments is a viable method of addressing the negative impacts of salinity in the soil. Saline soils have been shown to benefit from compost, manure, green wastes, and other organic amendments, which reduce the impact of erosive forces and improve soil structure and soil function (Diacono and Montemurro, 2015). Additionally, organic matter aids in jump-starting biological and chemical processes, which can buffer the negative effects imposed by salt and help to increase nutrient cycling and availability (Rao and Pathak, 1996).

Adding organic matter helps maintain the soil ecosystem, which can improve soil physical properties through the stabilization of aggregates. Bacteria and fungi release various glue-like substances through their metabolic processes that contribute to the adhesion of soil particles, creating soil aggregates. Increases in organic matter in soils impacted by excess salts have been shown to increase soil porosity and aeration (organic matter has much the same effect in non-saline soils), resulting in greater infiltration rates and reduction in soil salt content when flushed with water that is low in soluble salts (Diacono and Montemurro, 2015).

In other experiments, under saline conditions, the addition of poultry manure and compost has been shown to increase available potassium. The addition of soluble and exchangeable potassium (K+) acts in a similar capacity to calcium and magnesium; that is to say, under sodic conditions, potassium will compete with sodium for space on the soil particles. What's more, K+ plays an important role in the physiological function of plants, which can buffer some of the detrimental effects of salt stress (Diacono and Montemurro, 2015).

Mitigating Saline Conditions: Mulching

Mulches effectively limit the amount of salt accumulation on the soil surface because they reduce evaporation from the soil surface by 50% to 80%. Mulches can take various forms and can be used in a number of ways. Plastic cover and organic mulches are both effective options. Although both plastic and organic mulches are viable options for the reduction of salt accumulation, there are associated costs and benefits to both. Plastic mulches may require lower management

Considerations: Manure and Composted Manure

Avoid adding raw or composted manure to fields with crops that are highly sensitive to salt—especially dairy manure, which is typically higher in salt content (Lloyd et al., 2016). In well composted or aged manure, salt loads will be much lower than in fresh manure, and it may be added on a case-by-case basis. Testing of these amendments for salt content is recommended prior to application.

Composted dairy manure has some benefits to soils, but soils should be monitored for salinity if there are repeated applications of this type of compost. Photo: Rex Dufour, NCAT

and labor cost than organic mulches, but they are less effective than organic mulches when it comes to reducing salt accumulation (on average, 32% less salt accumulation on organic mulches) (Aragues et al., 2014). Plastic mulches can intercept precipitation, which reduces any potential leaching effect from rainfall. Plastic mulches also deteriorate over time and require disposal (Aragues et al., 2014). Organic mulches, on the other hand, may decompose rapidly and need to be replaced more often. They also benefit the soil ecosystem by feeding it and promoting earthworm populations (Jodaugiene et al., 2010).

Considerations for Hoophouses

Soil under hoophouses will accumulate salts because rainfall cannot reach the soil surface. Growers should keep this in mind when planning hoophouse construction. There are two design options that can help to address this issue: having the hoophouse on skids or wheels so it can be moved if it appears that salts are accumulating, or designing the hoophouse so that the plastic tarp can be moved to allow rainfall through.

Bare soil, exposed to both the sun and wind, loses moisture more rapidly than mulched soil. Water evaporates, leaving a crust of salts behind.

The border between moist soil and the dry soil, which is beginning to accumulate salts. Notice the light-colored streak. Photos: Rex Dufour, NCAT

Promoting Plant Growth and Soil Remediation with Microbes

Certain naturally occurring microbial species have been shown to improve plant growth and remediate soils under salt-stress conditions (Kumar et al., 2019; Wang et al., 2020). Interesting research is being done to uncover the mechanisms at work and to identify the particular physiological effects that these microorganisms have on plants and the soil ecosystem. For example, when *Trichoderma harzianum* is used as a seed treatment, it has been shown to mitigate some of the stresses imposed on germinating seeds by excessive salt loads. Treated samples showed increased root and shoot growth, photosynthetic rate, and leaf area when compared to control samples (Rawat et al., 2012).

Short-Run Strategies that Can Be Implemented Now

Drainage: Strategic placement and use of drainage ditches located in-field and on property borders can help to alleviate salt-related stresses placed on particular areas of a field or property.

Drought-resistant crops and salt-resistant crops: Drought-resistant crops can help to diminish some of the irrigation requirements. Irrigation reduction is most useful during the dry season, when the likelihood of irrigation with saline water increases. Switching to more salt-tolerant crops can be a short-term solution to production woes caused by excess salts.

Grafting: Grafting can be used to increase plant resistance to salts, when salt-tolerant rootstocks are available.

Arbuscular mycorrhizal fungi (AMF) represent a large group of symbiotic fungi that form relationships with more than 80% of all terrestrial plants (Kumar et al., 2019). AMF have proven to be effective soil remediators and plant growth promotors that can be purchased commercially or mobilized naturally in the soil through the planting of symbiotic plant species (Nurbaity, 2014). Moreover, the relative abundance of these naturally occurring beneficial microbial populations (bacteria included) can be further facilitated through planting salt-tolerant crops and/or cover crops that can greatly influence the development and function of microbial communities in salt-affected soils (Wang et al., 2020). In saline soils, AMF help plants by improving water absorption, nutrient uptake, increased photosynthesis and adaptation to oxidative stresses (Kumar et al., 2019).

Concluding Thoughts

American agriculture is facing increasing challenges and experiencing severe climate events more often now than in the past. Farmers are having to deal with unprecedented droughts, flooding, and fires, as well as more erratic and extreme precipitation and temperatures. If we are to avoid the fates of the civilizations Marc Reisner noted in the introduction—Assyria, Carthage, Mesopotamia, the Inca, the Aztec, the Hohokam—we, as a society, must pay more attention to better managing our soils as the complex ecosystems that they are. Fortunately, we have more knowledge than ever before about how soils should be managed for soil health, and about the impacts of irrigation in arid environments.

Farmers who implement practices supporting soil health (see ATTRA's publication *Managing Soils for Water: How Five Principles of Soil Health Support Water Infiltration and Storage)* often see their farms positively transformed—ecologically and financially. Because of the changes these farmers have seen in their soils—and their bottom lines—many have become passionate proponents of practices that support soil health. Teaching the principles of soil health as core components of agricultural and agribusiness curricula will elevate the understanding and connection of soil health and resilience. Our water, our food, our health, and our future depend on healthy soils, which are the most complex ecosystems on the planet. Just as one would invest in barn maintenance, equipment, and farm worker training, it is critical to the future of farming that we also invest in our soils.

ATTRA Resources

Beneficial microbial species can mitigate many of the challenges presented in this article. Management practices that encourage the presence of beneficial microbes are discussed further in the following ATTRA publications:

- Drought Resistant Soil
- Overview of Cover Crops and Green Manures
- Sustainable Soil Management
- Managing Soils for Water: How Five Principles of Soil Health Support Water Infiltration and Storage

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Notes

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