THE UNIVERSITY OF ARIZONA
Cooperative Extension

az2150 July 2025

Understanding Nutrient Dynamics in Desert Soil

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Understanding soil nutrient dynamics is key to proper agricultural management and a significant determinant of crop quality and yield. While this is true for all soils, those in the arid regions of the world have their own unique management challenges. The majority of plants are made up of 17 chemical elements, which determine the structure and function of everything around us (Table 1). These mineral elements are considered "essential", and the majority of are acquired from the soil. The balance (carbon, hydrogen, and oxygen) are acquired by the plant primarily from air and water.

Nutrient Acquisition by Plants

Plants do not acquire nutrients by consuming mineral soil particles, but rather the elements and compounds that are released from soil solids (mineral and organic fractions of soil). Nutrients in the soil may be considered mobile or immobile, based on the association they form with the soil and water that reside within the pore spaces of the soil. Mobile nutrients often readily dissolve in water, creating what is called the "soil solution", and are actively moved into the root system as the plant takes up water in a process called "mass flow" (Figure 1). Alternatively, nutrients may move towards roots in a process called diffusion, in which nutrients move from areas of high concentration to areas of low concentration. Nutrients that exhibit lower mobility form loose associations with the soil itself, though there is a constant exchange of nutrients between individual soil particles and the soil solution. Some nutrients, such as phosphorus, are relatively immobile in the soil. When this is the case, the plant must expand its root system in order to intercept nutrients where they occur in the soil.

Plant roots do require oxygen to function properly. Soils that lack good structure (the arrangement of soil particles that influence the capacity to facilitate the movement of air and water) and porosity may limit a plant's ability to take up nutrients. The macro- and micro-pore spaces should be balanced for optimum fluid dynamics in soil, i.e., air and water movements.

Table 1. A list of Essential Elements for plant growth and crop production (adapted from Weil and Brady, 2017).

	Element	Source	Common Plant-Available Form
Macronutrients (>0.1% of Dry Plant Tissue)	Carbon	Air	CO_2
	Hydrogen	Water	H_2O
	Oxygen	Air, Water	O_2,H_2O
	Calcium	Soil	Ca^{2+}
	Magnesium	Soil	Mg^{2+}
	Nitrogen	Soil	NH^{4+}, NO^{3-}
	Potassium	Soil	K^+
	Phosphorus	Soil	H_2PO^{4-}, HPO_4^{2-}
	Sulfur	Soil	SO_{4-}
Micronutrients (<0.1% of Dry Plant Tissue)	Copper	Soil	Cu^{2+}
	Iron	Soil	Fe^{2+}
	Manganese	Soil	Mn^{2+}
	Nickel	Soil	Ni^{2+}
	Zinc	Soil	Zn^{2+}
	Boron	Soil	H_3BO_3, H_4BO^{4-}
	Chlorine	Soil	Cl^-
	Molybdenum	Soil	MoO_4^{2-}

Sources of Essential Nutrients

Most of the nitrogen on Earth occurs in the atmosphere as dinitrogen (N_2) gas (approximately 78% of the air we breathe), though this is unavailable to plants and animals. However, this atmospheric nitrogen is accessed through a process called nitrogen fixation, in which lightning and soil microorganisms change the N_2 gas into a form of nitrogen that can be utilized by plants (Flynn and Idowu, 2015). In natural terrestrial systems, organic matter (organisms and their residues) constitutes the majority of the nitrogenous compounds in the soil and is made available to plants as it is decomposed by soil microbes such as bacteria and fungi. Arid soils tend to have relatively low levels of organic matter due to limited plant growth and rapid microbial breakdown caused by warm soil temperatures. Because of this, and high agricultural demands,

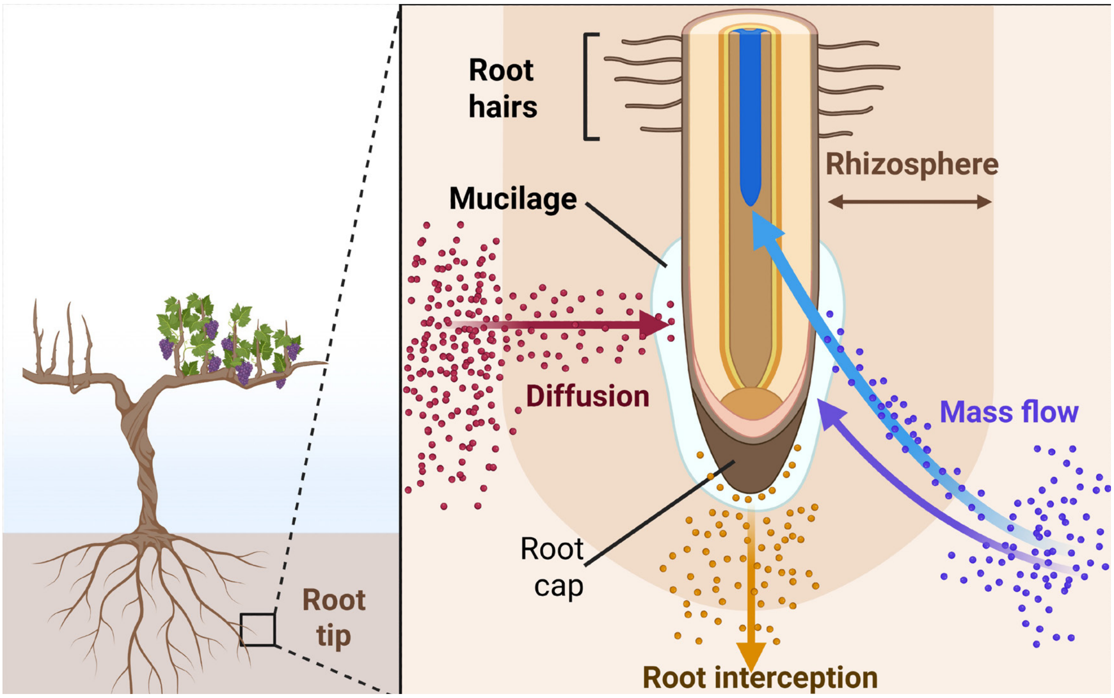

Figure 1. Diagrammatic presentation of Mass Flow, Diffusion, and Root interception, created in BioRender, Halldorson and Sanyal (2025) https://BioRender.com/2vxtgce.

synthetic nitrogen fertilizers are used in the majority of crop production systems worldwide.

The remaining elements are provided by the mineral soil itself, released from parent material (rocks, which were largely formed millions of years ago) as it is weathered to become progressively smaller particles. As nutrients are released from minerals such as quartz, feldspar, and mica, they may be incorporated into the "soil solution".

Nutrients in the Desert Soil

When considering soil-based nutrients, there are several unique characteristics of desert soils that must be taken into consideration. By definition, arid soils experience relatively low precipitation levels, and it is this, coupled with a relatively high cation exchange capacity (the ability of a soil to store and supply positively charged ions such as calcium), which dictates the pH and nutrient availability of desert soil.

While we commonly think of "salt" as sodium chloride (a.k.a. table salt) used to enhance the flavor of food, when referring to salts in the soil, we are actually referring to compounds and complexes of different nutrient ions (charged elements, polyatomic or monoatomic) that solubilize into the soil solution. The most common salts found in soils are made of calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K_{+}), sodium (Na^{2+}), sulfate, (SO^{42-}), chloride (Cl^{-}) carbonate (CO^{32-}), and bicarbonate (HCO_{3^-}) (Zamora, Tomasek, Hopkins, Sullivan, and Brewer, 2022). In arid, desert regions, salts accumulate in the upper soil profile because the lack of precipitation and gravitational water movement impedes the leaching of salts into lower horizons, while the greater evaporative demand (influenced by environmental factors like prolonged sunshine hours and low relative humidity) moves soluble salts through capillary pores in the soil that ultimately deposits salt in the topsoil profile. Irrigation is another common reason that detrimental levels of salts accumulate in the soil. When a field is irrigated, the minerals dissolved in the irrigation water are also transported to that field. As the water applied to the soil surface evaporates, salts are left behind to accumulate (Figure 2). The accumulation of any type of salt in soil can be

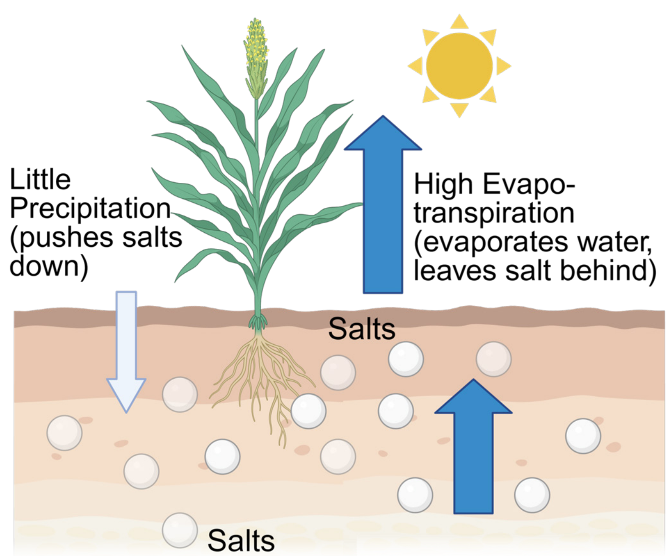

Figure 2. Soil salinization in the desert region is predominantly caused when water is evaporated and consumed by the plants, while the salts precipitate close to the soil surface, resulting in soil salinization, created in BioRender, Halldorson and Sanyal (2025) https://BioRender.com/s5k1clo

Figure 3. The white layers are calcite or caliche, which are often found in Arizona soils (Idowu and Flynn, 2015).

detrimental to crop production, as it interferes with the plant's ability to uptake water. There are a few different classes of salt-affected soils.

Calcium (Ca^{2+}), in particular binds with carbonates in the soil solution to form calcite (CaCO3), an insoluble compound that precipitates and increases pH to and above 8.2 (Figure 3). If the pH of any soil is measured to be 8.2 or greater, there is a high probability that calcite is accumulating in the profile. Calcite can also cause permeability issues when it precipitates in large quantities to form what is commonly referred to as a "caliche (pronounced kah-lee-chee) layer". Caliche can be deleterious to plant growth because it can impede root growth and water movement through the soil (Walworth and Kelly, 2002).

Classification of Salt-affected Soils

Soils are classified as saline if they have sufficiently high levels of salts (often calcium and magnesium) to adversely affect plant growth (an electrical conductivity value greater than 4 dS/m or mmhos/cm; dS = decisiemens; mmhos = milimhos) but are not dominated by sodium salts (have an Exchangeable Sodium Percentage of less than 15) in particular. These types of soils have pH values no higher than 8.5 and do not usually suffer from a lack of infiltration and poor structure, though an accumulation of white crust may be visible on the soil surface.

Sodic soils are characterized by high levels of exchangeable sodium, though not necessarily high overall levels of other salts. One of the key characteristics of sodic soils is that they often have much higher pH levels than saline soils due to the fact that sodium does not precipitate as readily with carbonates as calcium and magnesium. These high sodium levels lead to poor soil structure primarily due to slaking (breaking of soil aggregates), and dispersion (dispersed soil particles block pore spaces, eventually compacting the soil). This loss of structure often leads to low levels of oxygen in the soil, limiting plant productivity. Improving sodic soils can often be achieved by applying gypsum (calcium sulfate) or elemental sulfur, which also effectively lowers soil pH.

Ultimately, salt accumulation and the resulting high pH contribute to nutrient imbalances (Weil and Brady, 2017). The micronutrients copper, iron, zinc, and manganese tend to become less readily absorbed into the soil solution under high pH conditions and often need to be applied in chelated (the encirclement of the nutrient by a less reactive compound)

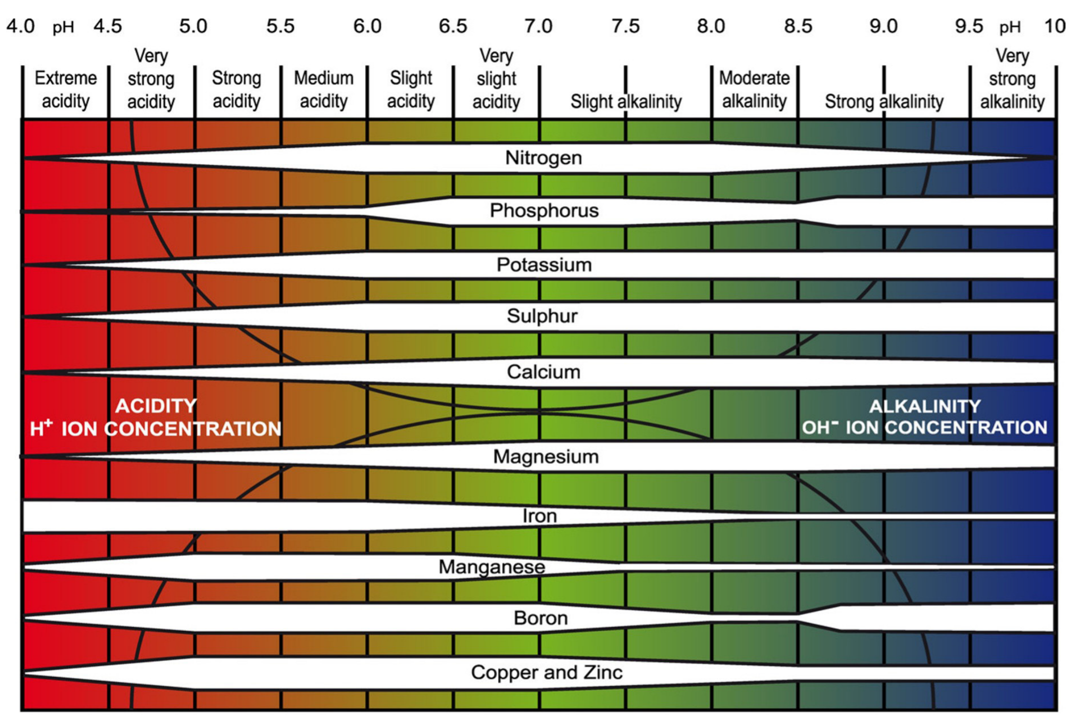

Figure 4. Nutrient availability is dependent on soil pH (*adapted from Potash Development Association*).

forms by farmers. Boron deficiencies are also common in both sandy and clayey soils, especially those with low levels of organic matter. In many cases, it is advantageous to apply minerals by foliar methods of delivery in agronomic or horticultural systems (Walworth and Heerema, 2019). Plants may also suffer from phosphorus deficiencies in arid lands due to the fact that high levels of salts such as calcium and magnesium tend to bind to phosphorus-containing compounds such as phosphate, causing them to fall out of the soil solution. Conversely, the micronutrient molybdenum is highly available in high pH soils associated with floodplains, and may lead to toxicity issues related to copper acquisition in ruminant animals.

Recommendations for Desert Growers

Due to their unique characteristics, desert soils require special considerations regarding resource management. Low precipitation, which leads to an accumulation of salts eventually drives an increase in soil pH and nutrient deficiencies and structural issues. Therefore, producers in Arizona are often recommended to conduct:

- Soil testing*
- Plant tissue testing*
- Irrigation water testing*
- Judicial fertilization
- Smart application of amendments, which either displace (e.g., gypsum) or bind (e.g., organic matter) salts

*See University of Arizona Extension publication AZ1111 and AZ1111s for a non-exhaustive list of testing resources.

Acknowledgement

This work is partially funded by a grant from the Specialty Crop Block Grants funded by the Arizona Department of Agriculture, SCBGP# 24-26.

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