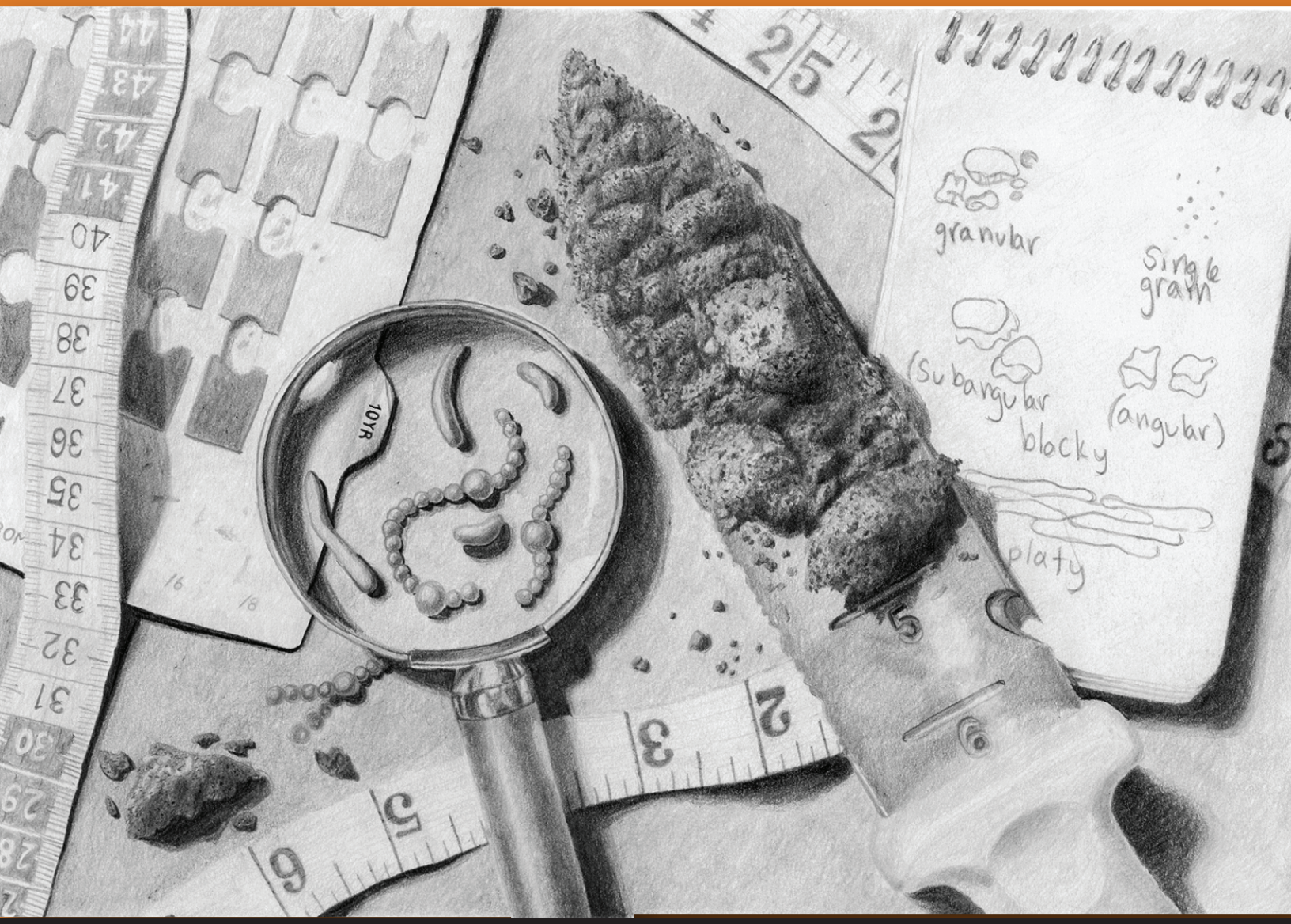
# Introduction to Soil Science

## 2nd edition

Amber Anderson and Rivka Fidel




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# Introduction to Soil Science, Second Edition

# Introduction to Soil Science, Second Edition

Amber Anderson and Rivka Fidel

Iowa State University Digital Press
Ames, Iowa

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*Iowa State University is located on the ancestral lands and territory of the Baxoje (bah-kho-dzhe), or Ioway Nation. The United States obtained the land from the Meskwaki and Sauk nations in the Treaty of 1842. We wish to recognize our obligations to this land and to the people who took care of it, as well as to the 17,000 Native people who live in Iowa today.*

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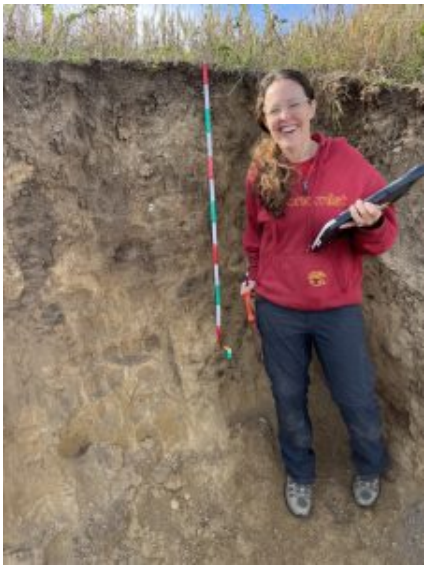
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# Introduction

**Amber Anderson and Rivka Fidel**



Welcome soils students!



Amber in her preferred habitat. Photo Credit: Lee Burras.



Rivka teaching soil science laboratory [Photo property of The University of Arizona | CC-BY-SA]

**Dr. Amber Anderson** is an Associate Teaching Professor at Iowa State University in the Agronomy Department as well as coach of ISU's soil judging team. She is looking forward to sharing her knowledge of soils and interacting with those of you both at Iowa State University and beyond.

**Dr. Rivka Fidel** is an Associate Professor of Practice in the Department of Environmental Science at the University of Arizona. Like Dr. Anderson, she got her PhD in Soil Science at Iowa State University, where she researched biochar (a charcoal-like soil amendment) while developing a passion for teaching and outreach.

To students at UA and ISU, and learners everywhere: wishing you a fun and fruitful learning journey!

We want to acknowledge the contributions, review, and support of Abbey Elder, Dr. Lee Burras, Dr. Cole Dutter, Dr. Bradley Miller, Heidi Ackerman, Dr. Ala Khaleel, Arturo Flores-Godoy, Ada Subora, Elizabeth Severson, Francis Akitwine, Becky Wokibula, Hallie Sandeen, Kai O'Connell, Casey Luke, and many others at Iowa State University Department of Agronomy. Thank you to external reviewer Sam Indorante and other instructors who have sent helpful comments. Cover illustration by Audrey Jenkins.

PART I

# Getting Started

CHAPTER 1

# Function of Soils

**Amber Anderson**

## Learning Objectives

- Define soil and soil science
- Discuss soil functions
- Summarize the importance of soil

**Keywords:** ecosystem services, soil science, soil functions

We may take what lies below our feet for granted, but soils are critical to our everyday life. From the food we eat, buildings we take refuge within, products we use, even to antibiotics we rely on, soils supply far more than we initially imagine.

## What is soil?

Several definitions exist. We will start with the pair below:

> "**The unconsolidated mineral or organic matter on the surface of the Earth** that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics."

— Soil Science Society of America[1]

> "Soil is **a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface**, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment."

— Soil Taxonomy, second edition [2]

Overall, we see the important components, a medium that supports a variety of functions on which plants and animals rely. These diverse functions can be grouped into a few major categories according to the Soil Science Society of America: products, resources, culture, and environment.[3]

## Products

Straightforward uses like the majority of food production, building materials like clay to make bricks, and unexpected items like many of the antibiotics that we rely on are all derived from the soil. In the case of plant growth, soil provides the physical structure, many nutrients, water, and insulation from changing temperatures that allow for plants to grow and produce.



Clay being harvested near Kamuli, Uganda, is being made into bricks in this oven on site. Photo credit: Amber Anderson.

## Resources

Holding water and carbon are also critical functions of soil. Consider a situation where the soil did not hold water for plant growth. Management and production of

1. US Department of Agriculture. (n.d.). Soil. Natural Resources Conservation Service. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/edu/?cid=nrcs142p2_054280
2. US Department of Agriculture. (1999). Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys. Second edition. https://www.nrcs.usda.gov/sites/default/files/2022-06/Soil%20Taxonomy.pdf
3. Soil Science Society of America. (n.d.). Soil Ecosystem Services. https://www.soils.org/files/science-policy/issues/reports/sssa-soils-eco-serv.pdf

crops would suddenly be far more complicated. Carbon is also important within the soil and will be covered in a later chapter of this book.

## Culture

While it might not be obvious, soils are also important for cultural aspects such as recreation. Central campus with its open space for enjoying nice weather, the intramural fields that host a variety of activities, or Reiman Gardens displaying a diversity of plants, flowers and artistic displays, all rely on soil properties and functions to exist.

## Environment

Additional benefits of soil come from the soil's ability to filter water, hold water to avoid flooding, recycle waste, and other ecological services. A variety of interactions will be covered over the course of this semester.

> Soil science, or **pedology**, is the study of this amazing resource.

I'm looking forward to sharing with you this semester, and looking forward to you sharing your observations as well!

### Check it out!

Soils don't all function the same, even for a similar use, or in a similar area:

- Soil Your Undies Challenge: Assessing your soil health[4]
- Marion county, Iowa comparison [PDF][5]

4. US Department of Agriculture. (n.d.). Soil Your Undies Challenge. Natural Resources Conservation Service. https://www.nrcs.usda.gov/conservation-basics/conservation-by-state/oregon/soil-your-undies-challenge

5. Neil Sass. (n.d.). Soil Your Undies for Soil Health. https://www.marioncountyiowa.gov/files/conservation/soil_your_undies_for_soil_health_70282.pdf

## Key Takeaways

- Soils are critical in a variety of different ways
- General functions can fall into production, resource, cultural, and environmental categories
- Wooo! Soil! Get excited to learn more about soil this semester!

PART II

# Soil Development and Classification

CHAPTER 2

# Parent Materials

**Amber Anderson**

## Learning Objectives

- Match depositional forces and the resulting material/properties
- Predict properties of an area based upon parent materials
- Identify potential management challenges based upon a given parent material

**Keywords:** Parent material, glacial till, outwash, alluvium, lacustrine, marine, colluvium, loess, aeolian sand, residuum

## Parent material

A **parent material** is the substance in which a soil develops. The properties of the original substance will significantly influence the resulting soil profile and properties.

## Transporting forces

Several different forces transport materials to the places we find them today. Sometimes, multiple forces combined to deposit the material, such as ice or gravity plus water. Other times, one force deposited a new material on top of an existing, like loess over glacial till, or alluvium over other material. High-energy transporters, like ice, don't sort the particles as low-energy transporters, like water and wind. Therefore, low-energy transported materials tend to be well-sorted, whereas high-energy transported materials tend to be unsorted.

## Ice

During past ice ages, parts of the central US were covered in thick sheets of ice. The massive weight

and power of these sheets ground down bedrock in Canada, transporting both small particles and huge boulders. This history of material deposition, along with the following prairie vegetation, have given Iowa the fertile soils present today.

## Glacial Till



Glacial till hill

This material was both carried and deposited by ice. Glaciers covered much of the northern part of the United States, and down into the Northeast corner of Kansas and northern part of Missouri in the central US. Since the ice crossed a variety of bedrock on its trip, these materials usually contain loamy textures (indicating mixed sand, silt, and clay), as well as assorted shapes, colors, and sizes of rocks. Management concerns could be related to the rock fragments found in the material.

## Glacial Outwash

This material was carried by ice but sorted by water as it was rushing out of the glacier. Small particles that could stay suspended in water, like silts and clays, were washed away. Larger particles, like sands and gravels, were sorted and deposited at the edge of the current glacier. Management concerns may include low water or nutrient holding capacity. Deposits of outwash can be found across the same region as glacial till, but in pockets or slopes across rather than across a widespread area.



Outwash profile in Northwest Iowa



Close up of outwash profile, Northwest Iowa. [Photo Credit: Amber Anderson]

## Water

Water is considered a low-energy transporter, leading to sorted materials. These could be coarse or fine. These might have alternating layers if periods of high and low flow normally occur.



The alternating horizon color shows that water was a transporting force in this soil. [Photo Credit: Amber Anderson]

## Alluvium

Alluvium deposits are formed from running water, as might be found next to a river. Since the size of the material potentially transported is highly dependent on the speed or energy of the water, these are well sorted materials. They can also change in short distances both vertically or horizontally, as rivers may move or carry different amounts of water over time. Alluvial deposits can be found near streams or sometimes upland drainageways, generally on the flat part of the landscape or steps above the stream or channel. Management concerns could include active flooding or may differ in short distances across the field.



This soil, found on the Kansas river flood plain, shows significant recent deposits burying the prior surface. These materials are relatively unchanged since deposition. [Photo Credit: Amber Anderson]



Stony alluvium in Costa Rica indicates very fast-moving water when these were deposited. [Photo Credit: Amber Anderson]

## Lacustrine

Lacustrine materials were deposited in lake environments. Since these were former lake beds, they tend to occur on lower parts of the landscape and be relatively flat. Rivers flowing into lakes may be carrying significant sediment, but larger materials are dropped as soon as the water enters the lake and slows. Therefore, lacustrine deposits are generally composed of smaller particles, such as silts and clays. As water flowing into the lake has periods of higher and lower flow, small alternating layers can frequently be found in the C horizon of these deposits as can be seen in the photo. Management concerns are likely related to the fine textures and low/wet part of the landscape.



Pictured is an example of lacustrine parent materials. [Photo Credit: Amber Anderson]

## Marine

These deposits are found along former coastal areas, not necessarily where coasts exist today. Fertility may be a concern since materials remaining after water movement may be high in resistant minerals like quartz, which is low in weatherable plant nutrients.



This marine-derived soil profile was found in Arkansas. [Photo Credit: Amber Anderson]

# Gravity

## Colluvium

Colluvium is highly variable, as it depends what was uphill at the time of deposition. These are most commonly found on current or former footslopes, where material slowed down due to the decrease in slope.



Recent colluvium in Ames, IA, due to destabilization of the soil surface. [Photo Credit: Amber Anderson]

Management concerns may be stability of the landscape or vary based upon the uphill material's properties.

# Wind



Wind has shaped this landscape next to the Platte River, near Grand Island, NE. [Photo Credit: Amber Anderson]

## Loess

Loess is wind-blown silt materials. Western Iowa is known as one of the deepest accumulations of this material, in the Loess Hills. These deposits are generally both fertile and highly erodible, leading to need for careful management. As one moves away from the source, the depth thins and the texture becomes finer. Across the state of Iowa, this means a shift from over 100 feet to just a few feet, while the texture shifts from silt loams to silty clay loam textures. The material may appear slightly yellow, as seen in the photo.



Loess showing irregular erosion pattern as water moves through a surface small feature, like animal burrow, and removes additional material. Locally, near Maywood, Nebraska, these were called 'jugs' and were indicated to get 'large enough to swallow a side by side or horse'. [Photo Credit: Amber Anderson]



Thick loess exposure found in western Iowa south of Sioux City. [Photo Credit: Amber Anderson]

## Aeolian Sand

Aeolian sand can be found downwind of a source, such as near a sediment heavy river, especially during periods of low water flow when the sediments would be exposed. These are generally found closer to the source, and are fine sands rather than larger or mixed sands, due to the weight of the sands-coarse sands being too heavy to transport in the wind column.



Aeolian sand bedding layers, found near North Platte, Nebraska. [Photo Credit: Amber Anderson]



Aeolian deposits rising above the flatter floodplain of the Platte River near Grand Island, Nebraska. [Photo Credit: Amber Anderson]

## Residuum

Soils with a parent material of residuum form into bedrock that was brought to the surface. In some cases, that may be at significant depths as in highly weathered tropical conditions found in the picture (left). In conditions where less weathering has occurred, it may be found at shallow depths. Properties are based upon the original parent material properties, like sandstone resulting in a soil with low water and nutrient holding capacity, but high aeration.



This profile in Southern Ghana is due to weathering of bedrock, in spite of no bedrock physically being present within visible depth. [Photo credit: Andrew Manu]



This shallow profile in Northern Kansas was not able to be dug more than 2 feet thick due to the solid bedrock underneath. The upper part of the profile was derived from the underlying sedimentary bedrock. [Photo Credit: Amber Anderson]

## Organic accumulation

Occasionally noted in soil descriptions, some surface materials are due to organic accumulation. This may occur when anaerobic conditions have prevented decomposition at a rate equal to plant production. If drained, as in the picture on the right, decomposition can occur and **subsidence** may be a significant concern.

Found in a lacustrine area in NE Minnesota, the upper portion of the profile pictured below is organic accumulation due to previous lack of decomposition. In some cases, this can be tens of feet thick, and be the primary material into which a soil can develop.



This area was drained for peat harvest. [Photo Credit: Amber Anderson]

### Key Takeaways

- Soil materials can be deposited by a variety of forces under different conditions
- Depositional differences (high energy, low energy) influence the resulting soil properties
- Parent material properties can significantly influence management concerns

CHAPTER 3

# Soil Development

**Amber Anderson**

## Learning Objectives

- Identify soil forming factors
- Relate factors to increased or decreased rate of soil development
- Predict how soil profiles change over time or space

**Keywords:** weathering, soil forming factors, material, topography, organisms, climate, time

## Soil Development

Soil develop, or weathering, is the amount of change that has occurred since the material was originally deposited. In order to get change, energy is put in, materials are added or taken away. Rainfall moving through the soil may carry away calcium; plant growth may add organic material to the soil; biological as well as physical interactions change the soil structure; clays may accumulate or break down.

## Factors

A variety of factors influence the amount of change that has occurred since deposition. Generally referred to as soil forming factors, the following five aspects of a soil's history significantly influence what it looks like today.

> Watch this overview video at: https://iowastate.instructuremedia.com/embed/71f7214c-ffb0-4f58-abfd-65dc4e604911

## Material

The type of material makes a significant difference in the rate of development. One example is a loose material, like glacial till, compared to a shale bedrock. As the material receives rainfall, water can move into the loose material, whereas the shale will take first breaking up the material before it can start the same process. Water can move more easily through (and therefore change) sands and other loose materials, so loosely cemented material (like sedimentary sandstone) and very hard materials (like slate) will be slowest to change, given other factors identical to this.

## Topography

While material may be consistent across an area, the same hillslope will not develop or change at the same rate. Stable upper parts of the landscape will have water moving through them, changing the profile (moving or transforming clays, carbonates, etc), and the organic-rich surface or residues are likely to stay in place. In the steeper slopes, water may run off or erosion may remove the top layer of soil. Additionally, low parts of the landscape may receive deposits from above (erosion) or below (flooding) and then need to start developing or changing those materials. Therefore, holding other factors equal, we see the most development on the stable upper portion of the landscape.

## Organisms (including humans)

Organisms can have a significant impact on changes. In former prairie regions, like across Iowa, areas where prairie dominated have or had A horizons of significant thickness with less developed B horizons, whereas areas where trees dominated are more likely to have an O-A-E-Bt or A-E-Bt horizon sequence. Humans drastically alter the landscape and soil processes as well, moving A material, removing cover that significantly increases the rate of erosion, compacting soil (on purpose for structural support or unintentionally), to name a few.

## Climate

Since energy to change a soil and reactions require both moisture and warmth, warmer and wetter conditions lead to more development. Changes are slow or non-existent if the soil is in a frozen state-as water can't move through, biological activity is minimal, and chemical reactivity is generally decreased.

## Time

As one might expect, more time since deposition means more time for changes to occur. Therefore, time is a significant factor, with more time leading to more development if other factors are the same.

## Key Takeaways

- Soils change over time
- The five major soil forming factors that influence soil development are parent material, topography, organisms, climate, and time

CHAPTER 4

# Soil Orders

**Amber Anderson**

## Learning Objectives

- Distinguish basic features of the 12 NRCS soil orders

**Keywords:** classification, soil order

## NRCS Soil Taxonomy

This system organizes soils into twelve major groups, or orders, that each end in -sol. Orders are determined by major climate factors, dominant materials, or degree of weathering. Underlined letters are what is used to indicate that order in further classification.

- **US map of soil order extent**[1]

> Watch this overview video at: https://youtu.be/0mCaCFUxM9Q

1. US Department of Agriculture. (n.d.). The Twelve Orders of Soil Taxonomy. Natural Resources Conservation Service. https://www.nrcs.usda.gov/resources/education-and-teaching-materials/the-twelve-orders-of-soil-taxonomy

## Gelisol

These soils, found under permafrost conditions, have unique features from the freeze-thaw cycles. They are quite challenging to build on, but interestingly, can have organic accumulations due to slow decomposition.

Cold temperatures are the most limiting factor for plant growth.



[Photo Credit: Amber Anderson]

## Histosol

These soils form when organic matter accumulates rather than decaying. Common areas to find them include saturated conditions, where organic matter is unable to decompose due to anaerobic conditions. Northeast Minnesota contains some of these soils, as does parts of Florida.

Limitations for plant growth are likely whatever is slowing organic matter decomposition, like an extremely shallow water table.



Histosol in a lacustrine area. This area had been drained for peat harvest, and would otherwise be submerged.

## Spodisol



[Photo Credit: Amber Anderson]

These soils are formed from organic matter complex with a metal like aluminum and move down in the profile. They are found under conditions that allow for movement-generally under acidic vegetation and sandier or coarse materials. In the US, these are found in the Northeast, Northern WI and MI, as well as parts of Florida. Challenges for management are likely fertility.

## Andisol



This organic vegetable farm is on volcanic ash in Costa Rica, a volcanically active area.

These soils are derived from volcanic ash, giving them unique structural and chemical properties. They are quite stable (see farm in picture found in Costa Rica), until saturated. The amorphous crystal structure also changes chemical and physical properties. In the US, these are found in the Pacific Northwest.

## Oxisol

Deeply weathered and dominated by iron and other resistant minerals, these soils are only found in the most weathered conditions on Earth-near the tropics where warm and wet conditions dominate along with long-term stability in the soil surface.

These soils can have meters and meters of B horizon materials, with no C or R within diggable depths. Fertility is more dependent upon the rapid decomposition of the prior crops than the soil releasing weatherable minerals.



Amber examining an Oxisol in Southern Ghana. [Photo Credit: Andrew Manu]

## Vertisol

Vertisols are challenging soils to manage. Composed of high amounts of shrink-swell clays, these soils crack when dry, and swell up when wet. This can crack roads or foundations built upon these soils without proper precautions.

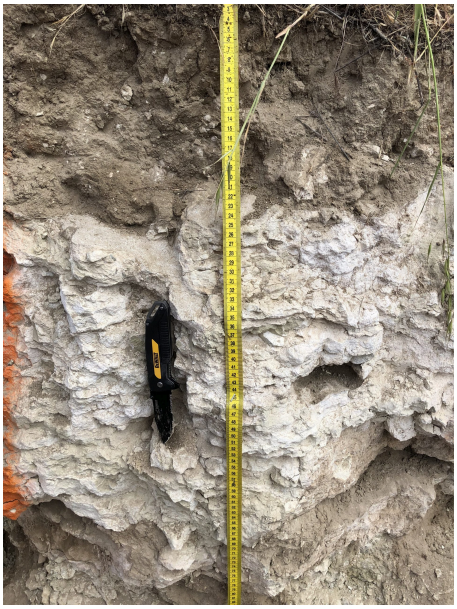


ISU soil judgers examining a vertisol in Southern California near San Luis Obispo. [Photo Credit: Amber Anderson]

Fenceposts in the picture above are tilted, in spite of it being a recent installation. Field operations have

a narrow window between too wet and too dry. If excavating, these are also unstable, so should be shallow with wide access.

## Aridisol



This aridisol in Southern California has significant calcium carbonate accumulation, cementing soil particles together. Unconsolidated soil can be seen under this cemented layer. [Photo Credit: Amber Anderson]

These are soils in arid conditions that contain developed features (not shifting sands). The low rainfall means materials can accumulate, such as the significant amounts of calcium found in this example. Water is the primary limiting factor for plant growth in these soils. In the US, these are found in the Southwest.

## Ultisol



This soil near Martin, Tennessee, shows characteristic red colors common with more red soils, along with having the base saturation needed to be characterized as an ultisol. [Photo Credit: Amber Anderson]

These are highly weathered soils, but not to the extent found in the tropics. They have low base saturation (associated with low fertility) and have many of their weatherable minerals removed. In the US, these are found dominantly across the Southeastern states.

## Mollisol



This central Iowa soil has almost 80 cm of dark soil (far more than minimum for a Mollisol) before redox features are visible. [Photo Credit: Amber Anderson]

These soils are characterized by the depth and color of the A horizon, an indicator of organic matter accumulation. Found dominantly under areas with prairie as their native vegetation, these soils are generally quite fertile. Limiting factors for crop growth may be wetness or limited growing season. In most cases, 25 cm of colors with value and chroma 3 or less are required, along with high base saturation.

## Alfisol



This soil face shows both an E and Bt horizon, indicating a movement of clay from the upper portion to the lower. [Photo Credit: Amber Anderson]

These soils generally have a Bt horizon, but still a high base saturation, generally associated with higher fertility. They generally have an E and Bt horizon, indicating a movement of clay from the upper portion to the lower. If under an established forest, they may also have an O horizon.

## Inceptisol

These soils are young, but show some development. They normally have an A-Bw-C or similar horizonation, showing weak development in the lower profile. These may be found on stream terraces, where soils are fairly young, but no longer being flooded.

They also may be found in areas that lack sufficient rainfall, time, or temp to have changed the soil from the time of the last deposit.



This soil face has young development and shows weak development in the lower profile. [Photo Credit: Amber Anderson]

## Entisol

These are underdeveloped soils. Recent deposition or instability mean that the soil hasn't had enough time to change since deposition. These are common along flood plains, and can be found in other unstable areas, where erosion or deposition has removed the prior soil horizons.



This soil, found on the Kansas river flood plain, shows significant recent deposits burying the prior surface. These materials are relatively unchanged since deposition. [Photo Credit: Amber Anderson]



This soil, found at the base of a hill in Iowa, shows evidence of recent instability uphill, as the surface 25-30 cm are on top of the prior surface. [Photo Credit: Amber Anderson]

## Key Takeaways

- 12 major soil orders exist in the US system of soil taxonomy, by either degree of development or special cases
- These broad categories are based upon degree of weathering (change from when deposited) or special circumstances.

CHAPTER 5

# Soil Classification

**Amber Anderson**

## Learning Objectives

- Understand structure of both NRCS and FAO classification systems
- Discuss major soils features given a classification at the great group or subgroup level

**Keywords:** classification, soil order, suborder, great group, subgroup, reference soil groups

## Classification

As for classification systems of living organisms, classification for soils helps organize our knowledge and communicate important information. Different systems have been developed in different countries, so in this section we will cover the basics of the classification system commonly used in the US, as well as the younger world reference base classification.

## Using the system

This system works on the first-fall out principle, accept whatever order you cannot reject first when moving down the list as ordered above.

- **Order**—most broad group, 12 options (e.g., Mollisol, Entisol)
- **Suborder**—adds one more distinct trait, usually related to water/climate (e.g., udoll, aquent)
- **Great group**—adds another trait for a total of three syllables (e.g., hapludoll, fluvaquent)
- **Subgroup**—additional trait (e.g., Typic Hapludoll, Aeric Fluvaquent)
- **Family**—adds temperature, mineralogy, and textural info (e.g., Fine-loamy, mixed, superactive, mesic Typic Hapludolls)

- **Series**—locally described soil with a range of properties and horizons within a described range: (e.g., A Clarion series is a Fine-loamy, mixed, superactive, mesic Typic Hapludoll)

Watch this overview video at: https://youtu.be/sQ8O4rTF9cY

## World Reference Base Classification system

The international classification system, developed more recently than the NRCS system, to create an 'international units' for communicating soil properties globally. This system incorporates aspects of several national systems, including the US and Russian systems.

Instead of soil orders, 32 reference soil groups (RSG) are used instead of soil orders. Principal and supplementary qualifiers are used to communicate additional information.

- View full WRB documentation and versions online[1]

### Key Takeaways

- Soils are classified by major features, generally that impact management
- Classification helps us to communicate significant amounts of information quickly

1. World Reference Base. (n.d.). FAO soils portal. *Food and Agriculture Organization of the United Nations*. https://www.fao.org/soils-portal/data-hub/soil-classification/world-reference-base/en/

PART III

# Soil Physical Properties

CHAPTER 6

# Soil Texture

**Amber Anderson**

## Learning Objectives

- Define soil texture
- Match the three major sizes of particles to influences on other soil properties
- Given percentages of sand, silt, and clay, provide a textural class
- Predict potential management concerns with a given textural class

**Keywords:** Sand, silt, clay texture, textural class

## Soil particles

Watch the overview video at: https://www.youtube.com/watch?v=80DmbTZyWr4

## Particle sizes

### Sand

The largest of the fine soil materials since anything larger is considered a rock fragment. Like marbles, these particles don't fit tightly together, leading to plenty of space for air and water to move through. Normally, this means good drainage and higher gas exchange for roots. Don't assume that a sandy soil will be dry though, as even a sandy soil at the water table will have water-filled pores. Think of a beach when the tide is high; the sand is wet or under water, but when the tide goes out, the sand can quickly drain.

## Silt

These are medium-sized particles, that generally feel soft and like flour. While they are considered more erodible and low strength for building purposes, they are generally favorable for plant growth. A higher percentage of water held in this soil is available for plants, and these are normally younger soils with weatherable minerals to provide some fertility for plant growth. Erosion can be a significant challenge to manage in a high-silt soil.

## Clay

These are the smallest particles, and generally feel 'sticky' to the touch. The surface area per gram is significantly higher than sand, leading to more ability to interact with other things in the soil, such as water. Think of clay more like sheets of paper in a book; there is a lot of surface area in a given weight or volume and it would take a long time to dry out or move water through. While they hold significant amounts of water, not all is available for plant uptake. Timing field operations, providing aeration, and improving drainage can all be challenging aspects in a clay soil.

# Textural Class

Textural classes group soils with similar sand, silt, and clay amounts into categories that help with management decisions. While we may say 'clay' as a particle, a 'clay texture' requires over 40% of the soil to be in the clay-sized particle range. Generally, the most important word for management is last, with modifiers added to the front.

For example, consider a sand, loamy sand, and a sandy loam. Following the axis at the bottom of the triangle, we see that a sand needs at least 85% sand, whereas a loamy sand needs 70% and a sandy loam could have as low as 45% sand if it also has low clay. We would therefore expect the management challenges associated with the sand-sized particle, like low water holding capacity, to be most limiting in a sand, followed by a loamy sand, and then a sandy loam.

> Watch the overview video at: https://www.youtube.com/watch?v=jBEzgvxHC5A

## Links to Learn More

Visit the NRCS Soil Texture Calculator[1] to calculate a single point texture for soil class based on the percent of sand, silt, and clay.

## Key Takeaways

- Particles are grouped into sizes: sand, silt, and clay
- Each particle is associated with different soil functions or properties
    - Sand is associated with high aeration, low water and nutrient holding capacities
    - Silt associated with low strength and high erodibility, but high available water
    - Clay is associated with high nutrient and water holding capacity, low aeration
- Texture is an important factor for determine function and management challenges for a soil

1. NRCS. (n.d.). Soil Texture Calculator. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167

CHAPTER 7

# Soil Horizons

**Amber Anderson**

## Learning Objectives

- Match soil horizons with processes occurring within the zone
- Identify horizons given characteristics
- Predict potential management or use challenges based upon given horizon sequence

**Keywords:** Horizons, development, subhorizons

Watch the overview video at: https://www.youtube.com/watch?v=BUt9gAvb_1o

## Horizon overview

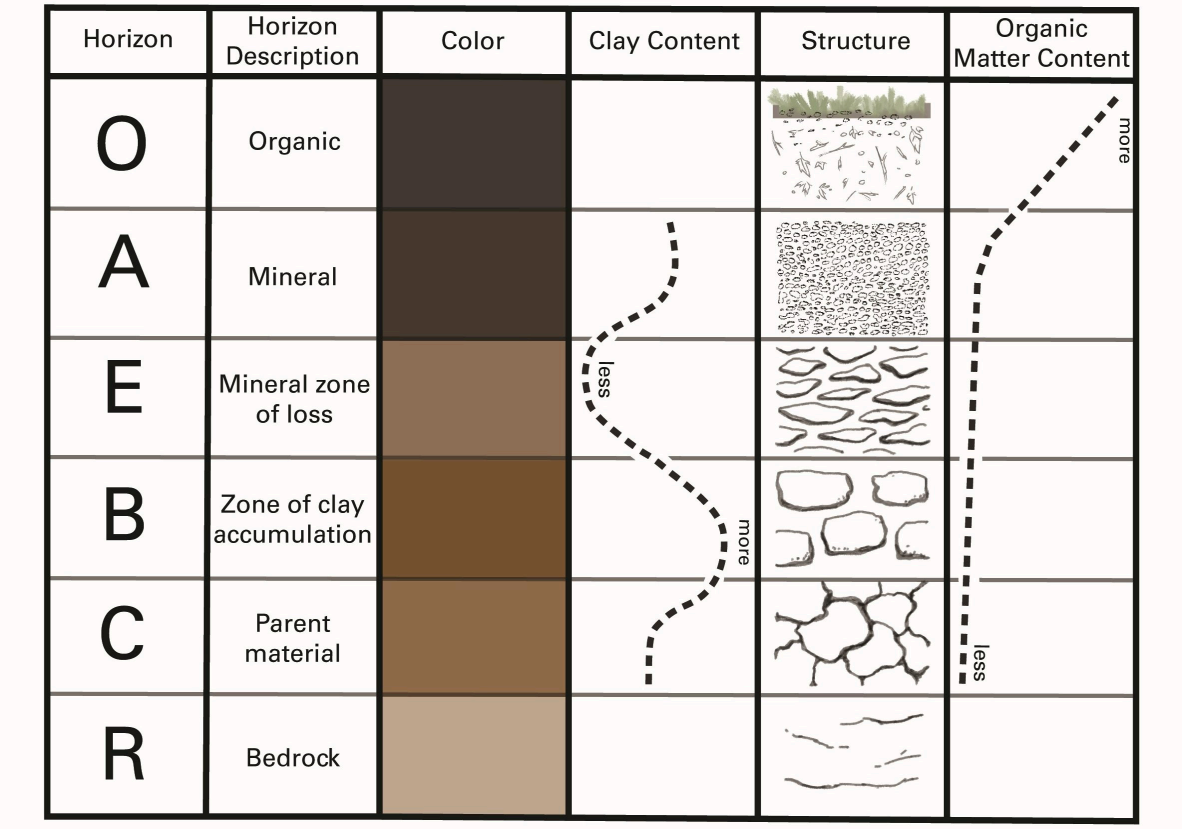



*Illustration by Madeline Schill, 2021,* in Soils-Iowa's Nature Series.

## Transition horizons

Sometimes a layer is not clearly one process or another, but rather where two are combining. These are called transitional horizons, and indicated by two capital letters like AB or BA. The first of the two is the more dominant of the two processes. A similar-looking notation but with an added /, like E/B or B/E mean that there are distinct areas of each in the layer rather than a smooth transition.

### Check it out!

Visit the NRCS Official soil series description page to find a soil series description and the horizons found in that soil. **Hint**: see if your name or home town/favorite town in the US have their own soil series.[1]

## Subhorizons

Additional lowercase letters are used to further differentiate horizons.

> Watch the overview video at: https://youtu.be/XrN68MEAy4M

**Check it out!**

Descriptions of all horizons and subhorizons used in NRCS classifications can be found on page 46–51 in the *Field Book for Describing and Sampling Soils*.[2]

## Numbering

In order to distinguish one horizon from another, numbers at the end indicate multiple of the same zone, split by other differences like structure, redox features, or color.

Numbers at the beginning of the horizon indicate it is part of a different deposit or parent material. Because we might not know how many exist or be able to dig down far enough to find all parent materials, we start numbering from the surface even though the older deposit is on the bottom.

1. Natural Resources Conservation Service. (n.d.). *USDA-NRCS Official Soil Series Description View by Name*. https://soilseries.sc.egov.usda.gov/osdname.aspx

2. Natural Resources Conservation Service. (n.d.). *Field Book for Describing and Sampling Soils*. https://www.nrcs.usda.gov/resources/guides-and-instructions/field-book-for-describing-and-sampling-soils/

## Key Takeaways

- Horizons are general concepts used to describe the major process(es) happening in the layer
- Not all horizons are found in every soil, sometimes multiple of the same horizon are found in one profile

CHAPTER 8

# Soil Structure

**Amber Anderson**

## Learning Objectives

- Identify soil structures and factors influencing their development
- Predict what structure might be present given additional information such as soil conditions or horizon
- Explain how structure may impact plant growth or other soil functions
- Predict how management factors might impact structure

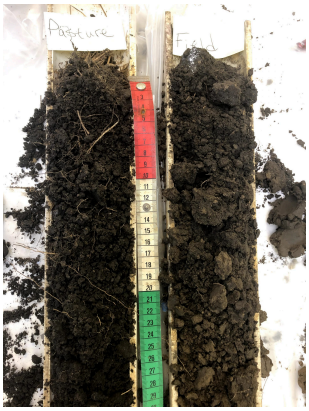
**Keywords:** Structure, aggregation, granular, platy, blocky, prismatic, columnar, massive

## Structure

Soil structure is the shape in which soil particles group together and form aggregates. A soil aggregate, or conglomerate of sand, silt, clay, and sometimes organic material, may be a variety of different shapes.

Structure is important because it allows critical areas of open space, vital for water to move, roots to grow, and soil organisms.

Consider a classroom or the space in which you are currently viewing this: when the materials are put together effectively, it allows space for interactions. If only a pile of building materials, the space doesn't serve the same function.




Even in the same soil or area, management practices can influence structure. [Photo Credit: Amber Anderson]

Watch this overview video at: https://www.youtube.com/watch?v=lZoXBe8mqpc

## Factors influencing aggregation

A variety of factors influence how soil particles aggregate or group together. Biological activity, organic addition, wetting/drying cycles, freezing/thawing cycles would be expected to increase aggregation, whereas tillage, compaction, and chemical properties such as sodium would decrease aggregation.

## Shapes

### Granular

These rounded groups of particles don't pack together well, allowing more space for water to move through. They are most commonly found in A horizons with higher levels of organic matter, healthy root growth, without significant compaction.



This forest A horizon has primarily granular structure, with a few small blocks.

### Platy

Commonly found in E horizons, the natural breaks in this soil are horizontal rather than vertical. These are easily destroyed by tillage. Note that this is different from 'plates' formed by operating equipment when a soil is wet. Although they look somewhat similar, this structure is naturally formed over time.



Although fragile, platy structure can be seen here, especially around 7-8 cm as the lines in the soil run horizontally rather than vertically.

## Blocky

Blocky structural units are common to find in a B horizon or cultivated A horizon. They can be grouped by either angular blocky having sharp angles likely found in higher-clay soils, or subangular blocky, the more rounded corners.




The impact of tillage can be seen here, with more blocky structure found in the right, cultivated core, while more granular structure is found on the left core, taken from a permanent pasture.

## Prismatic

These have longer natural breaks vertically in the soil rather than horizontally. As was the case with this large prism in the photo, they are generally found in B horizons. Water and roots in this soil will likely move preferentially through the breaks between these units.



A very large prismatic structural unit found in NW Minnesota.

## Columnar

Columnar are a special type of structure created when sodium impacts a prismatic structure. A 'muffin top' or 'popcorn' looking appearance on the top of a prism develops from sodium dispersing particles. These are agronomically challenging soils to manage. Both water and roots will likely have problems moving through this soil easily.



Columnar structure on a sodium-impacted soil in South Dakota. Significant sodium accumulation above the orange nail, around 25 cm of depth.

## Massive or Single grained

These units of 'non structure' indicates there has been limited changes to this soil since deposition. In glacial till materials, a large piece will likely break between the points of pressure applied, rather than falling apart on pre-determined lines.

A midwestern soil at perhaps five feet of depth may not have developed structure because this takes something acting on it. Roots, freeze-thaw, wetting-drying and other factors are less active here, slowing down changes.

For single-grained soils, a lack of fine particles or organic matter means that there are not significant forces to hold sand grains together. This is an effect you may have seen in a sandbox or beach, as a small disturbance will cause the sand to fall apart to individual grains.



This soil has been recently deposited, and has not had time for structure to develop, so would be classified as massive.

## Management Impacts

Since plant growth tends to increase soil structure, more plant growth tends to lead to a better structure. In prairie ecosystems, a strong granular structure is expected.

Tillage can have negative impacts on soil structure, particularly when done in poor (generally too wet)

conditions. Consider the building construction of the earlier example in this discussion. When being built from that pile of building materials, a wall is removed or damaged, so this must be rebuilt first, slowing down progress.

## Key Takeaways

- Structure is important as it indicates the arrangement of soil particles
- Soil structure can change over time due to changing conditions or disturbance
- A variety of shapes exist, these tell you where water and roots are likely to move along those natural breaks
- Management has an impact on soil structure

CHAPTER 9

# Soil Color

**Amber Anderson**

## Learning Objectives

- Identify major factors contributing to soil color
- Outline how to use a munsell soil color book
- Use the soil color to potential challenges to management for a given use

**Keywords:** Color, hue, value, chroma, Munsell soil color book, redox features

Soil color is one of the first properties many people identify when asked to describe a soil. Although we may think of it as uniform, soil color can change quickly, both when moving down into the soil and across the landscape. These changes can be indicators of important processes happening in the soil. For example, grey colors may indicate wetness, and it therefore may not be a good place to construct a basement.

Major factors contributing to soil color include accumulation of organic material and accumulation of materials. This is described in more detail below.



Unique soil colors found in Tennessee. [Photo Credit: Amber Anderson]

## Accumulation of organic material

Accumulation of organic material turns the soil darker, as is commonly found in the surface layers. This may be several feet in some prairie-derived soils as pictured to the left, or even the whole visible depth, especially in cases like a floodplain or footslope receiving additional materials.



This image shows a large accumulation of organic matter in the top horizon.



[Photo Credit: Amber Anderson]

## Redox reactions

Redox, short for reduction-oxidation, is due to changes in soil oxygen levels, generally from having water-filled pores rather than air-filled pores. Oxygen diffuses slowly through standing water, and microbial activity can use up existing supplies causing reduced or anaerobic conditions.

If the reduced iron reaches oxygen, like a root channel or near the top of the water table, it will oxidize, creating a red spot in the soil. These spots are visible even in dry conditions, providing a record of normal conditions, regardless of recent rainfall.



Strong redox features are present in this ped. [Photo Credit: Amber Anderson]

## Accumulation of materials

Accumulations of materials, such as calcium or gypsum, can also color soil in certain circumstances. In the case of calcium or gypsum, white colors appear, frequently in the B horizon in semi-arid conditions or places on the landscape where water moves in carrying calcium, gypsum, or other salts, and evaporates off. Since the salts cannot evaporate, they remain in the soil.

In semi-arid regions, rainfall is sufficient to carry materials, such as calcium, out of the surface layer, but insufficient to leach materials completely out of the profile, leading to an accumulation generally in the B horizon.



White calcium accumulation in the B horizon of soil.

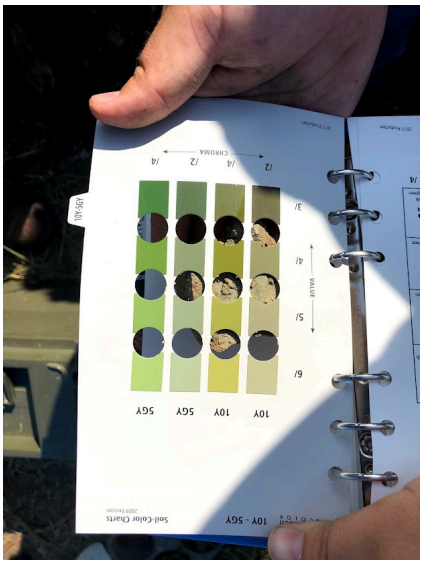
## Munsell soil color book

Since simple color description works like “dark” or “red” won’t mean the same thing to different people, soil scientists use a standard notation to indicate a soil’s color.

Soil color is formatted this way: Page/Value/Chroma

Example: 10YR 2/1

- **Page:** mix of colors or hue
- **Value:** lightness or darkness
- **Chroma:** intensity




Holding a ped under the Munsell Soil Color Book helps identify the color of the soil, as demonstrated in the pictures.

## How to use a Munsell Soil Color book

Watch this overview video at: https://iowastate.instructuremedia.com/embed/3f0f8ff0-f570-4635-8df1-0d1ce0ced869

### Key Takeaways

- Color is important as it indicates potential processes occurring in the soil
- Accumulations of material, redox reactions, and minerology impact observed colors
- The Munsell soil color book is a tool used to standardize soil color across locations

CHAPTER 10

# Bulk Density/Idealized soil

**Amber Anderson**

## Learning Objectives

- Identify what components might be found in an idealized soil
- Discuss impacts of compaction and management
- Calculate bulk density when given appropriate measurements

**Keywords**: bulk density, compaction, available water, unavailable water, pore space

## Idealized soil

> Watch this overview video at: https://www.youtube.com/watch?v=iDx45_h23SM

## Bulk Density

Bulk Density is the oven dry weight of the soil over the total volume of the soil. Since we expect particle density to be somewhere around 2.65 grams/cm3, in an idealized situation with 50% pore space, we would expect bulk density to be about half of that value. Bulk densities significantly higher slow or stop root growth.

> Watch this overview video at: https://youtu.be/2UTwNJqmv0w

## Compaction

Watch this overview video at: https://youtu.be/ixgtfZu1ZZk

### Key Takeaways

- An idealized soil has a balance of pore space filled with air, available, and unavailable water
- Compaction has a variety of negative impacts if managing for plant growth
- Bulk density is a measurement of soil density, and high values may be helpful for building but stop plant growth

CHAPTER 11

# Soil Subhorizons and Diagnostic Features

**Amber Anderson**

## Learning Objectives

- Compare and contrast epipedons, subhorizons, and diagnostic features
- Identify common subhorizons, epipedons, endopedons/diagnostic features

**Keywords**: soil horizons, subhorizons, epipedons, endopedons

As discussed in the previous chapter, horizons can be assigned additional designations for significant features or implications for management found in that layer. They can also have designations for major features found both at the surface and below. We use the terms epipedon, diagnostic subsurface horizon, and subhorizon to describe additional information not captured in the main horizon designation (O, A, E, B, C, R) of a soil.

To get started, note the following definitions:

- **Diagnostic horizon** = layer of soil whose properties meet certain criteria specified for the purposes of soil classification, i.e. a horizon with key features used to identify the soil type
- **Epipedon** = one or more contiguous surface soil layer(s) with shared features
- **Endopedon** = one or more contiguous subsurface soil layers(s) with shared features
- **Horizon designation** = letters assigned to horizons to denote their properties

Note that any given diagnostic horizon can include multiple horizon designations.

# Terms and Examples

## Diagnostic Epipedons

**Diagnostic epipedons** refers to surface layers of a soil with key identifying features. Major diagnostic epipedons include:

- **Mollic:** Generally thick, dark soil with high base saturation (aka nonacid cation saturation, see cation saturation percentages chapter), indicating significant organic matter accumulation, commonly found in prairie areas or where organic material accumulates
  - Composed of one or more **A** horizons
- **Umbric:** Similar to mollic, except with a low base saturation
  - Composed of one or more **A** horizons
- **Histic:** Primarily organic rather than mineral in the surface layer
  - Composed of one or more **O** horizons
- **Anthropic:** Significant human alteration, like human-transported material found at the surface
  - Composed of one or more **A** horizons
- **Ochric:** Doesn't meet other epipedon diagnostic characteristics
  - Composed of one or more **A** horizons

> - See more information and pictures in the NRCS's Illustrated Guide to Soil Taxonomy.[1]

## Diagnostic Endopedons or Subsurface horizons

**Diagnostic endopedons** are groups of one or more adjacent subsurface horizons with distinguishing features. These are other significant features in the soil but below the surface layer. There are many options, but here are a few:

1. Soil Survey Staff. (2015). *Illustrated guide to soil taxonomy, version 2*. Lincoln, Nebraska: U.S. Department of Agriculture, Natural Resources Conservation Service. https://www.nrcs.usda.gov/sites/default/files/2022-06/Illustrated_Guide_to_Soil_Taxonomy.pdf

- **Argillic:** Significant illuvial clay found in this layer
  - Composed of one or more **B** horizons
- **Albic:** Significantly leached horizon, grey or light color due to loss rather than wetness
  - Composed of one or more **E** horizons
- **Calcic:** Significant calcium accumulation
  - Composed of one or more **B** horizons
- **Glossic:** A special form of **E** and **Bt** that has 'tongues' of the illuvial (E or albic) materials reaching down into the illuvial horizon. The B horizon portion can be argillic, kandic or natric.
- **Lithic** or paralithic contact: Bedrock (hard or soft) found within profile
- **Natric:** Significant sodium salt accumulation, with illuvial clay accumulations
  - Composed of one or more **B** horizons
- **Spodic:** Subsoil layer(s) with accumulations of organic matter and/or dark colored minerals
  - Composed of one or more **B** horizons
- **Cambic:** Weak development (ex: minimal illuviation); doesn't meet diagnostic characteristics for other diagnostic subsurface horizons
  - Composed of one or more **B** horizons

- Many more exist, view them here at the NRCS Illustrated guide to soil taxonomy[2]

## Subhorizon

**Subhorizons** are further indications of processes happening within a layer, usually identified in the field. These may correlate to further diagnostic horizons or features, but may not have the corresponding lab data to support the higher designation. An example would be a Bt vs an argillic horizon: the "t" is a subhorizon meaning illuvial clay, so the described saw clay films when they described the soil. An Argillic means the presence of significant illuvial clay, generally defined by the NRCS as 1.2x the overlying clay for most soils. In most cases, these two would be described in the same zone, but it is possible to have less significant increase, resulting in a Bt not qualifying to be argillic. Similar differences could be an E that doesn't qualify as albic due to color requirements, or Bk that doesn't qualify as calcic.

2. ibid.

| Subhorizon letter | Usually found on what main horizons | Field indicator |
|---|---|---|
| p | A | plowed or disturbed, potentially a plow-line, compaction due to tillage or human activity, other indicators possible |
| g | E, B, C | gleyed (grey) color due to wetness |
| w | B | weak development, not clearly falling into one of the other subhorizons |
| t | B | clay films |
| ss | B | slickensides, where shrink-swell clays have slid against each other at intersecting angles |
| k | B | white masses or coats that fizz with HCl |
| y | B | white masses of gypsum crystals, don't fizz with HCl |
| x | B | fragipan, silica cemented root restrictive layer |
| r | C | appears to be like bedrock, but diggable with hand tools |
| d | C | dense/root restrictive layer |

| Subhorizon | Field indicator required | If significant with lab data, this horizon could be: |
|---|---|---|
| Bt | clay films | Argillic |
| Bk | white material that fizzes with HCl | Calcic |
| Bn | columnar structure or halophytic vegetation | Natric |

## Examples

The below soil profile has both argillic and calcic endopedons. Each endopedon has multiple horizons, and the endopedons overlap with each other. The horizon designations for this soil (from top to bottom) are:

1. A
2. Bt
3. Btk
4. Bk

The Bt and Btk subhorizon designations are part of the argillic endopedon; the Btk and Bk subhorizon designations are part of the calcic diagnostic horizon.



This profile in NE Kansas shows both slickensides (lower part of profile) and calcium carbonate accumulations in small root channels (above) in addition to the living roots.

## Key Takeaways

Note the following definitions:

- **Diagnostic horizon** = layer of soil whose properties meet certain criteria specified for the purposes of soil classification, i.e. a horizon with key features used to identify the soil type
- **Epipedon** = one or more contiguous surface soil layer(s) with shared features
- **Endopedon** = one or more contiguous subsurface soil layers(s) with shared features
- **Horizon designation** = letters assigned to soil layers to denote their properties
- **Diagnostic endopedon** = group of one or more adjacent subsurface horizons with distinguishing features
- **Diagnostic epipedon** = surface layers of a soil with key identifying features

Check with your course instructor to see if you additionally need to know the properties of specific diagnostic horizons, and at what level of detail (this information is included in open-book and/or bonus questions only at Iowa State University and the University of Arizona).

PART IV

# Soil Geography

CHAPTER 12

# Geography

**Arturo Flores and Bradley Miller**

## Learning Objectives

- Discuss the concept of geography.
- Understand the relationship between geography and soil science.

**Keywords:** geography, human and physical geography, spatial distribution.

## Introduction to geography

The most basic form of geography answers to "Where are things located." However, it is more complex and dynamic than that. **Geography** is the science that studies the Earth's surface and the phenomena occurring in it from a spatial perspective. It explores 'where' phenomena occur and tries to explain the 'why' it occurs there. Geography studies single and independent features, like geographic landforms and places, or complex events, like human migrations and soil type distribution.



World Map by Gerard van Schagen (1698)

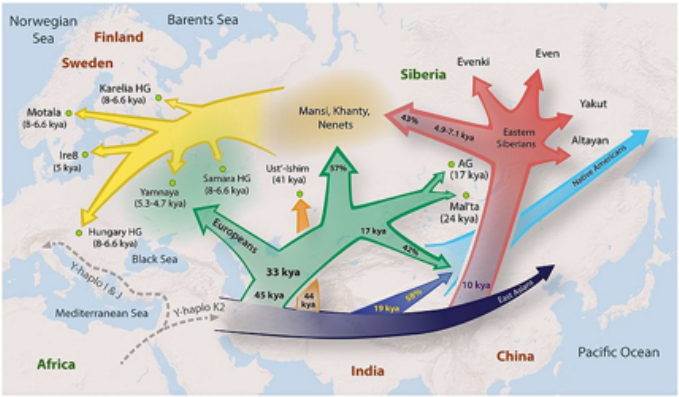
The geographic space includes a delimited area where natural elements from the environment (eg., rivers, mountains, vegetation, climate) interact with humans or with other environmental elements. In the beginning, human settlements and cultural expansion occurred to where natural

conditions where more favorable for agriculture, thus, for nourishment. Geographically speaking, soil fertility tends to be higher in alluvial systems (next to big rivers or regions prone to flooding). It was expected that cities would develop closer to this fertile land enriched with alluvial sediments brought in by water bodies, such is the case of the Egyptians in the Nile River and the Southern Asia cultures along the Mekong River. Higher precipitation rates and higher average temperatures throughout the year tend to facilitate and boost agricultural yield. Whilst the Norse struggled to grow few crops during the relatively 'warm' summer months in Greenland, people in Mesoamerica where able to harvest corn up to three times per year. This is the result of different geographical conditions, including climatic patterns and topography that regulate soil development and weather.

From a different point of view, more 'favorable' geographic conditions are not always so beneficial. Mayans exploited fertile soils so intensely, that soil quality decreased, fertility was reduced, and agriculture significantly limited to new deforested land through slash-and-burn systems. This caused massive Mayan migrations towards more 'fertile' land (south) and started a slow but constant decay of the civilization, leaving behind impoverished soils. Also, closeness to river systems may facilitate navigation and communication between cities. However, catastrophic flows have limited the rise of human settlements along them, such is the case along the Yangtze River basin in China. This shows how the geographical space is a 2-way system, in which natural elements and human distribution affect and are affected by their own action.

## Focus areas

Geography has two main focus areas: humans and the Earth. Human geography emphasizes human activities in the geographical environment, and physical geography focuses on the landscape and the process occurring in it. Yet, both try to provide an explanation for phenomena correlated with space and sometime with time as well.






LEFT: Example of Human geography map about the Eurasian expansion by Wong et al, 2017, CC BY SA 4.0.
RIGHT: Physical geography map representing the temperatures across the Unites States by Hinman, 1889.

## Human geography

**Human geography** is emphasized in the spatial distribution of people in respect to the natural environment. Some of the subdisciplines include cultural, economic, historic, political, and urban geography. It is commonly associated with social sciences because they work together to understand the human behavior. It differs from conventional social sciences in that human geography also includes the spatial dimension of the feature being studied. For example, economics is focused on understanding how the market operates, but economic geography also wants to explain how wealth and markets are distributed within a country. Embedded in human geography, some understanding of the landscape becomes useful to understand human distribution or cultural spatial patterns.

The landscape is all the visible space captured by the human eye at one specific moment in time. Each one of the shapes that exist in the landscape are called landforms, and some include mountains, volcanos, valleys, and plateaus. Because landforms regulate the flow of wind and water through the landscape and these are eroding and weathering factors, it is possible to conclude that landforms are the reason why landscapes are the way they are. However, the explanation for this is much more complex and requires a good understanding of the Earth's surface and processes. This is where physical geography takes place.

## Physical geography

**Physical geography** aims to explain why the landscape has a particular shape in the place where it is located. It is focused on all the natural features and processes shaping the Earth. To do so, physical geography needs to understand how the different environmental elements interact with each other and affect the Earth's surface. Hence, it studies the different layers that constitute the Earth: air, soil, water, and biology (atmos-, litos-, hydros-, and biosphere, respectively). Some of the subdisciplines include pedology, geology, geomorphology, hydrology, and biogeography. All of these emphasize the study of the physical features of the Earth and the dynamic interaction among them.

### Key Takeaways

- Geography studies spatial patterns of phenomena.
- Geography is not only applied for natural environments, but also in social sciences.

CHAPTER 13

# Cartography and Maps

**Arturo Flores and Bradley Miller**

## Learning Objectives

- Discuss the importance of maps for geography.
- Define the concept of geographic maps.
- Identify the different elements of a map.

**Keywords:** cartography, map, scale, legend, coordinates.

## Cartography and map creation

**Cartography** is a subdiscipline of geography that graphically represents geographic data on flat surfaces. The preferred method of geography to represent spatial phenomena is with maps. A **map** is defined as a flat representation of spatial phenomena. Maps support visualizing data that is linked to a specific location within a geographic extent. These are easily interpreted by the users and help explain how features are spatially distributed.

A person is seen on a desk using a contour finder to delineate a map from an photograph.

A person is seen on a desk using a contour finder to delineate a map from a photograph [Photo Source: "Map making circa 1943" by USMC Archives via Wikimedia, CC BY 2.0]

Maps represent topographic features (related to the landscape) or thematic themes (quantitative or qualitative data). Topographic maps represent landforms or geographic accidents in the landscape. Thematic maps include cities and roads, land use, soil properties, and even religions distribution. It includes the absolute location of a feature (position in the Earth's surface using coordinates) or a relative location (position using another object as reference). A map of a 10-acre farm with a pond next

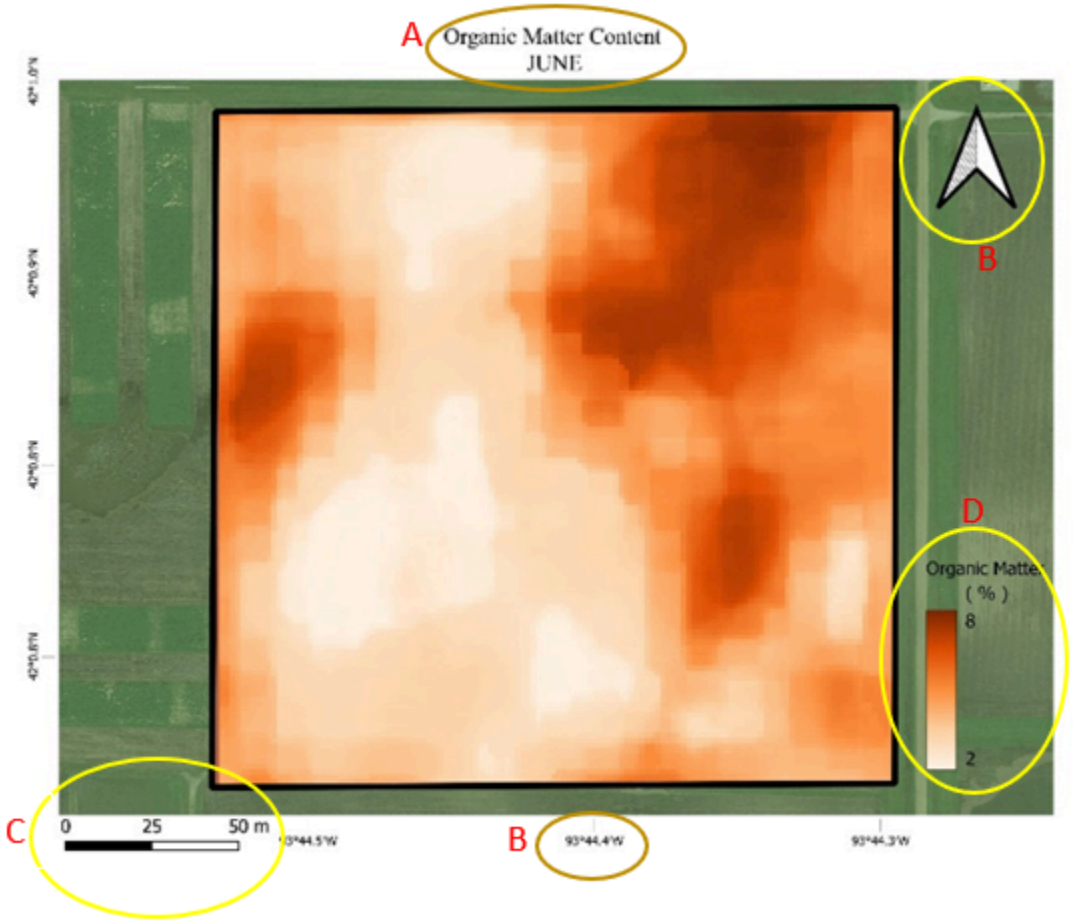
to a field may be useful to navigate through space locally. However, it will lack context about where that farm is located in respect to the world. On the contrary, a world map may provide the location of the farm on the Earth's surface but will fail to be a precise navigation tool when trying to locate features, e.g., the pond.

## Elements of a map

For a map to be efficient in transmitting spatial information, it has to include at least the following items:

- **Data.** Also, the actual map. It is the flat representation of the geographic space and the spatial phenomena occurring in it and is the most important part because without it the map would not exist.
- **Title.** The title is the first approximation of the user to the map's content. It should provide some background on what the map represents. The title "Organic Matter Content" provides enough information to know which soil property is being mapped. However, it may not be completely clear where this field is located for someone other than the author. Hence, other guidance is required.
- **Coordinates and Reference Point.** The coordinates help locate the geographic feature in the world. They are commonly included in the border of the map as ticks or as a grid overlaying the image. Different coordinates systems exist, and it should also be included in the map. A reference point can include a compass or arrow pointing towards the north, letting the reader situate itself better in the geographic space.
- **Scale.** A basic concept of cartography for paper maps (fixed map scale) is that the level of detail is dictated by the map scale. For example, if we made a map of Polk County, Iowa, it would make sense to delineate the city boundaries of Des Moines. In contrast, if we made a map of the world, we would only mark the locations of cities with dots and only include the largest cities. The scale explains the relationship between the map and the real world. It describes the ratio at which an area was reduced to be fitted on the map. For example, a scale of 1:100,000 means that 1 measuring unit in the map represents 100,000 units in the real world. Such units can be meters, centimeters, feet, yards, or even kilometers and miles. Small-scale maps cover big areas like the whole world, and large-scale maps cover smaller areas like farm fields. The level of detail present in small-scale maps is significantly lower than on greater scales. Large-scale maps can go as low as 1:1, but they would not be practical. Therefore, a scale of 1:5,000 can provide a good level of detail to navigate through the streets of a town. Small scales of around 1:1,000,000 can be optimal to represent a country boundary, perhaps not for precise land management but for a broad understanding of the region's physical geography.

- **Legend.** A map without a legend provides little context on what the visuals represent. A legend is a reference guide to decode the symbology of the map and includes a description of what each color or icon represents. Remember to include the units when quantitative values are mapped.




Map items: A) Title, B) Reference point and coordinates, C) Scale bar, D) Legend [Image Source: Arturo F.]

## Key Takeaways

- A map is the preferred tool of geography to share spatial data.
- A map should contain a title, a reference point and coordinates, the scale, and a legend for the reader to properly understand it.
- Images are not maps but can be used as base “maps” to reference and locate features in space.

CHAPTER 14

# Soil Geography

**Bradley Miller and Arturo Flores**

## Learning Objectives

- Define soil geography as a tool of soil science.
- Understand the importance of spatial variability of soil.
- Discuss the interest of soil science to create soil maps.

**Keywords:** soil geography, spatial variability, soil map, dynamic properties.

## Soil geography

If not all soil is the same and different soils have different capabilities, then it becomes important to know where these different soils exist. So, to match land use and management planning to the capability of soil, we need to understand the spatial distribution of soils. In addition, the soil is changing. Some soil properties change faster than others and they are dynamic both in space and time.



LEFT: Soil heterogeneity across a corn field in Boone, Iowa. Notice the change in colors depending on the position on the landscape, especially the hillslope position. RIGHT: Soil variability in a forest trail in Crosby, Minnesota. Even on a 1 m2 of soil, it is possible to have diverse content of materials, colors, and possibly chemical properties [Photo Credit: Arturo F.]

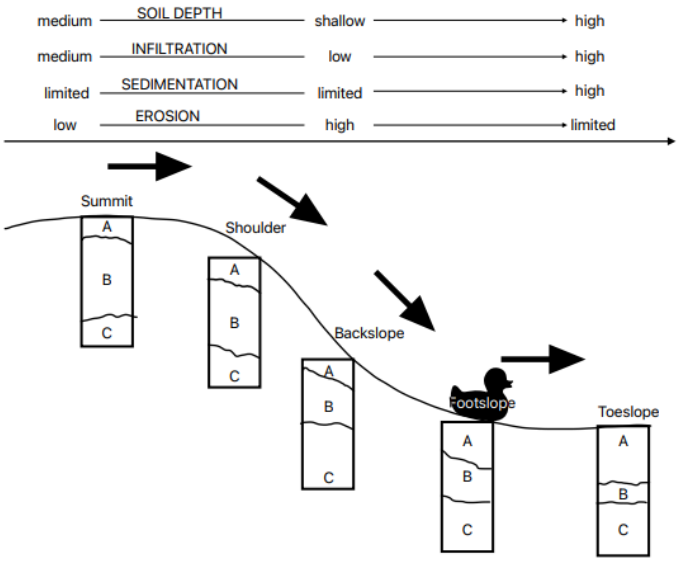
The spatiotemporal variability of soil is the result of different forming factors, weathering rates, time of development, and human intervention. It is known that soil not only varies vertically (soil profile), but laterally (across the landscape). Variability is easily observed from one place to another (macroscopic variability), or it can exist at a microscopic level. However, despite the level of detail at which soil is being evaluated, heterogeneity exists and is critical for land management. Therefore, it is possible for geography to study soil as a geographic unit.

Soil geography applies geographic principles into the spatial study of soil heterogeneity. Soil properties or characteristics are a response to their location. Soil forming processes occur differently across the landscape. The location of a point the geographic space is determinant for weathering intensity. The fundamental concept of 'catena' was explained by Geoffrey Milne, who defined it as 'the regular repetition of soil profiles in association with certain topography.' This concept captures the impact slope has on hydrology, and how the last serves as a critical factor for soil dynamics.

The most influential factor in weathering and sediment translocation is slope gradient. This is the inclination or degree at which a slope gains or loses elevation compared to the horizontal level. It can be measured in degrees (45°) or in percentage (100 %), meaning that a slope of 100 % has an inclination of 45 ° and gains one unit of elevation for every horizontal unit. Steeper slopes increase water kinetic energy and its erosive potential, whilst gentle slopes or almost level ground decrease the speed of water fluxes and increase material accumulation.

Convex slopes tend to be easily eroded from surface particles that accumulate more in concave regions. Higher deposition may be correlated with high enrichment areas as sediments carry nutrients along. However, they can also be problematic as water tends to accumulate more and optimal rooting

conditions can be limited. Slope orientation has a regulating effect on soil properties. Regions facing to the south (in the northern hemisphere) and to the north (in the southern hemisphere) are exposed longer to solar radiation. This results in higher soil temperatures that increase biological activity, production of biomass, and perhaps reduce the time soil remains frozen after freezing winters. Wind also impacts soil development, and the east-west orientation of the slope is therefore critical in wind erosion. Slopes facing directly to the wind current are more prone to suffer from erosion than slopes on the other side of the hill. Assuming that wind is flowing west to east, a slope facing west will be slowly depleted from fine surface particles and will end up with higher accumulation of coarser materials, whether opposing slope (facing east) might end up less disrupted and with more fine sediments.

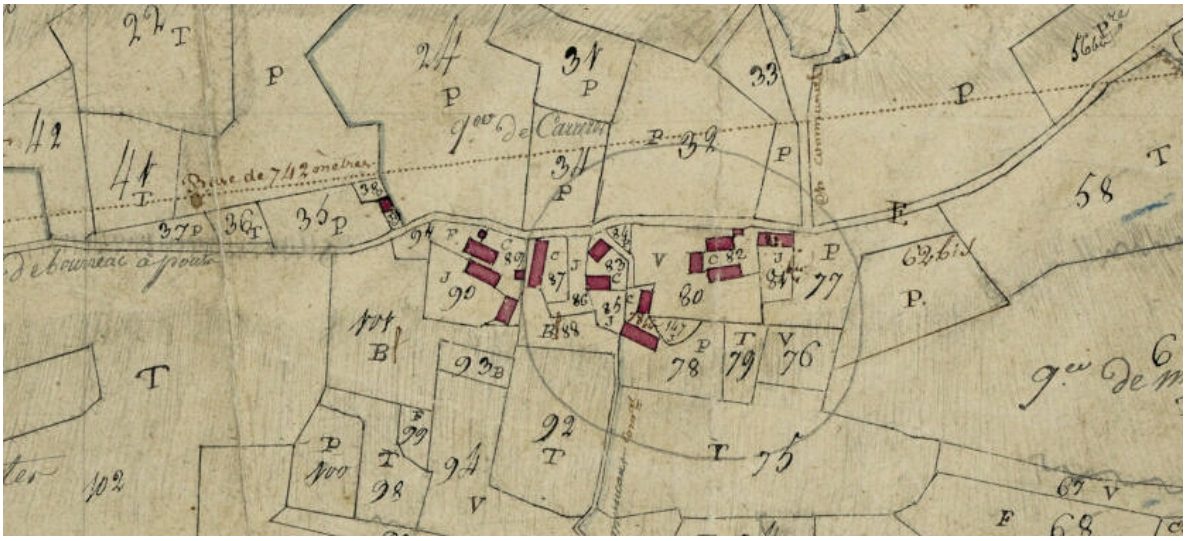



Graphic representation of the hillslope position effect
[Image Credit: Arturo F.]

The position on a slope will also determine the speed at which water can erode surface materials, the infiltration rates, and the accumulation of sediments. From top to bottom, hills can be divided into summit, shoulder, back slope, foot slope, and toe slope. The first two correspond to less slope steepness (inclination) and have higher infiltration rates. Where slope starts to increase, water potential increases and with it, runoff. The back slope is the steepest section of a slope, and this causes finer particles to be carried down through water fluxes (surface water erosion). This region does not allow much time to infiltrate and has higher translocation of finer materials. Therefore, back slopes have higher content of sand or gravel and less developed soil horizons. As the slope starts to settle, the foot slope and toe slope are located at the bottom of it. Here steepness is reduced and water potential decreases as its speed also is reduced. This causes the sediments to settle and increase the thickness of the surface materials, which can include silts, clays, and nutrients carried along. The previous image demonstrates the sections of a slope and what processes are more likely to occur in each one of them.

## Soil maps

We use soil maps for many things. The original purpose of soil maps was cadastral, which means land valuation for the purposes of taxation. The idea is that owners of land with more productive soil will have higher yields, higher income, and thus can afford to pay a higher portion of taxes. This use of soil maps is still common today for agricultural land. Another fundamental purpose for soil maps is interpretations for land use capability. Some of the earliest soil surveys were part of geologic reports and were essentially inventories of natural resources. This was especially common for colonies and other lands newly set up for settlement. In the early history of the USA, European settlers were setting up new farms and the soil survey maps provided guidance for which crops were best suited for that land. These reports were typically organized and paid for by county and state governments.



Napoleonian cadastral map from 1809 map of Recahorts Hautes-Pyrénées, France.

Another common type of soil map that serves a different purpose than soil survey maps are soil fertility maps. These soil maps focus on soil properties that change quickly and support decisions that are important to the annual economics of field management. To differentiate between long-term and short-term soil properties, we categorize them as static and dynamic soil properties. Soil survey maps focus on static soil properties because they are more reflective of the natural capability of a soil. Also, given that soil survey maps have taken a long time to create for the large extent they cover, they focus on soil properties that won't make the maps out of date only a few years after they are created. In support of the cadastral purpose of soil survey maps, focusing on the natural capability of soils avoids the variability in management. In other words, the taxation rate is based on standard management practices, not if the farmer is especially good or poor at managing their fields.

The dynamic nature of soil fertility properties makes them more challenging to predict. While the

factors of soil formation still apply, the relationship with those factors changes over time. For example, the application of a nitrogen fertilizer may level soil nitrate concentrations across a whole field. As time goes by, plants are consuming some of that nitrate and other biological processes are converting it to nitrous oxide gas (denitrification). While the plants may be taking up nitrate at spatially consistent rates, denitrification occurs at different rates depending on spatially variable factors such as soil water content. In addition, water moving through the soil leaches nitrate downward. Sometimes that leaching takes the nitrate straight down and sometimes that water transport is more lateral, causing the nitrate concentrations to decrease in the upper elevations and increase in the lower elevations. At any particular point in time, we could measure soil nitrate concentrations by soil sampling and identify patterns with respect to landscape position. However, as the nitrate migrates down the slopes the relationship with landscape position changes, which makes spatially predicting nitrate concentrations across the field a moving target.

## Key Takeaways

- Soil geography studies the formation and distribution of soil on the Earth's surface.
- Soil maps are representations of the spatial variability of soil at one specific moment in time.
- Dynamic properties (which change over time) become challenging to represent on a static map.

CHAPTER 15

# Mapping Methods

**Bradley Miller and Arturo Flores**

## Learning Objectives

- Understand how maps are created.
- Discuss two mapping methods.
- Define GIS and its importance and relationship with soil mapping.

**Keywords:** map delineation, spatial autocorrelation, spatial association, GIS.

## Creating a map

Thinking about the logistics of making a soil map, we must come to terms with how we map something that by definition exists mostly underground. Making an accurate road map is relatively easy since the advent of aerial photography. All one has to do is trace the roads that one sees in that image and then label them. Unlike road maps, soil maps are a game of spatial prediction. A soil mapper could poke hundreds of holes in the ground and still only directly observe a small portion of the soil landscape. Aerial photographs have played a key role in the creation of soil survey maps, but they don't let the soil mapper see much of the soil.

Traditional soil maps were created using the soil surveyor's knowledge, intuition, and understanding of the available soil information It is impossible for farmers to sample all locations within their fields because it is unpractical and time and cost expensive. To address this problem, maps are created by making predictions at unsampled locations based on scatter observations across the landscape. Soil sampling provides a broad understanding of the soil for that specific point. However, this knowledge is useful to identify patterns and relationships among soil properties.

## Spatial predictions

Our best clues for predicting soil properties come from the environment that they formed in. Recall the factors of soil formation that describe environmental variables that influence soil processes. Such factors were probably credited to Hans Jenny, but they were listed sixty years before that by Vasily Dokuchaev when he was describing how to map soil in Russia. Nobody had thought to use combinations of factors to predict soil variation. The environment, including topography, climate, and vegetation, may explain more about soil properties than we can think of. The ancient Greeks knew to look at the vegetation for clues and the German agrogeologists of the 20th century knew to look at texture and mineralogy for clues, but previously these were considered to be competing ideas.

## Spatial association

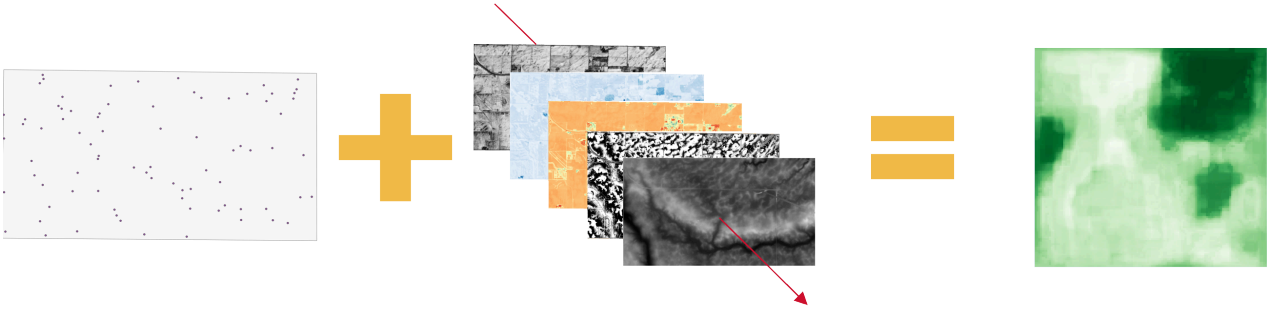
Utilizing the factors of soil information to associate patterns of soil variation is known as the soil-landscape paradigm. This is a specific example of the geographic concept of **spatial association**, which is that some variables covary with each other in space. By looking at variables that are more readily observed, one can infer variables that aren't as easily observed. In the case of the soil landscape paradigm, a soil mapper could observe soil properties in one location and infer that other locations with matching climate, vegetation (the part of organisms that can be seen in an aerial photograph), landscape position, and parent material would also have the same combination of soil properties. For example, the Clarion soil series is mapped on the tops of the gentle hills of the Dows geologic formation (region known as the Des Moines Lobe). Within a county scale map, climate doesn't change very much. However, there are measurable differences in climate across multiple counties. For this reason, the Clarion soil series is not associated with exactly the same soil properties from one county to the next. Although parallel in the other factors of soil formation, the Clarion soil series is associated with slightly different soil properties as observed in each county and the same is done for all soil series. This strategy allows for a general concept of soil series to be easily communicated, while also helping the county soil maps to be more accurate.

### Spatial association with a machine learning approach

Artificial intelligence is a power and modern tool that has supported and improved the creation of high-quality maps. The idea behind this method is make spatial predictions at unsampled locations by recognizing relationships between known values and some ancillary data (covariates).

Such covariates include topography, vegetation, satellite imagery or even other soil maps that

may provide enough background information to explain soil's behavior at the locations where predictions want to be made. Different machine learning algorithms arrange the data at a specific known location and associate it with the covariates for that same point. The machine learning algorithm fits a model over that data and help make predictions of unknown values at unsampled locations. The following image represents the process:



Use known locations where samples were taken and associated those values with covariates for that specific location. This way a model is fitted on the data and a soil map can be created based on spatial associations between the property being mapped and the covariates explaining its behavior [Image Credit: Arturo F.]

## Spatial autocorrelation

To make soil fertility maps, all the same basic principles apply for mapping something that we can only directly observe in a few locations while wanting to know the spatial distribution of that target variable across the whole map area. We still must predict the status of the soil belowground based on a small proportion of samples and whatever clues we can find aboveground. Because dynamic soil properties are changing quickly and with them their relationships to aboveground variables, soil fertility mapping tends to lean on a different geographic principle. This other principle is **spatial autocorrelation**, which means that things that are close together tend to be more similar to each other than things that are farther away. By this principle, two measurements of soil nitrate concentrations taken 3 feet (1 meter) apart are more likely to be similar that two samples taken 100 feet (30 meters) apart. Now, any soil scientist will tell you that you can be surprised by differences in soil cores taken almost side by side, and in the case of soil fertility you want to be careful not to sample on a hot spot where fertilizer was recently applied (e.g., the thin band produced by targeted side-dressing). However, part of being a dynamic soil property is being relatively more mobile than static soil properties and that lends to more diffuse spatial distributions. Not having hard breaks in concentrations works better for the spatial autocorrelation approach to mapping.

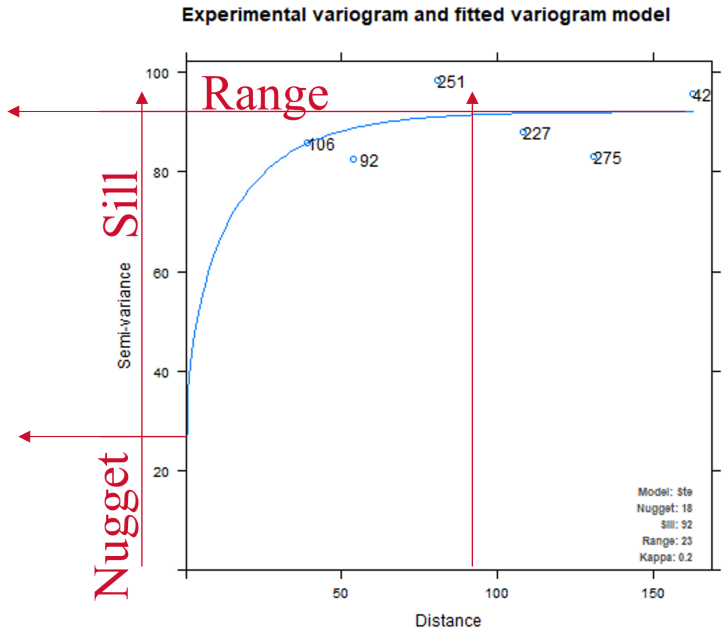
The most basic method for using spatial autocorrelation to create a map is to take the sample points and then draw polygons identifying the area closest to the respective points. This identifies the areas

that are likely to be similar to each of those measured points. Then we assign the measured value of each point to its respective surrounding area. In doing this, we are predicting values in an area based on the nearest measured location. A common practice in soil fertility mapping is to take soil samples on a regular grid, and then assign sample results to equally size squares surrounding each of the sample points. Although variability likely exists within those squares, if the squares are not larger than the size of area that a farmer can vary their management practices, then a finer resolution would not be useful.

In the era of precision agriculture, rates of applying soil amendments can be increasingly targeted. This means that a 2.5-acre grid (100 x 100 m squares) or even a 1-acre grid (60 x 60 m squares) may be too coarse of a resolution to supply the information needed to fully utilize the capabilities of precision agriculture. With the basic spatial autocorrelation approach described above, making a finer resolution map would require taking more soil samples. Instead of a sample in every acre, maybe management zones of 0.5 acre can have unique fertilizer prescriptions. In which case, a sample in every 0.5 acre would double the quantity of samples needed. However, spatial autocorrelation can be more useful than single value blocks. Spatial interpolation uses the concept of spatial autocorrelation to predict a smoother gradient of values in between observed locations. Within a geographic computer-based software, algorithms such as inverse distance weighting (IDW) or kriging can create prediction surfaces at any resolution the user specifies.

## Spatial autocorrelation approach (variogram)

The variogram is the statistical tool used with kriging methods to predict values at unsampled locations based on distance from a known point. It tells how much two samples can vary based on the distance that exists between them. The range is the distance at which the variogram levels off and points at this distance or farther apart are not spatially correlated. The nugget effect is a representation of the small-scale variability, and the sill is the maximum variability between a pair of points. In this example, a model was fitted into a variogram while performing an ordinary kriging analysis for Phosphorus content in the soil. The model fitted into the variogram is telling us how much the data is expected to vary as the distance from a point starts increasing (lag distance in x axis).




Variogram showing the range, the sill and the nugget [Image Credit: Arturo F.]

## Geographic Information Systems (GIS)

The acronym GIS stands for ***Geographical Information Systems***. GIS is the implementation of software and hardware for the storage and manipulation of spatial data. Digital geographers combine computing power and computer-based analysis to store, modify, analyze, and present geographic data using digital maps. Its capabilities allow users to even tie non-spatial data to a specific location and obtain geographical results. For example, a list of coffee shops does not provide much information beyond the name of each and probably an idea of what they sell. However, if a set of coordinates is assigned to each of those names, it is possible to locate them in space and navigate towards each.

To store and manipulate data, GIS utilizes layers of information to simplify the process. Each one of these layers includes objects with georeferenced data (data assigned to a fixed location), and values (quantitative or qualitative). Objects include:

- **Vector data**, or discrete objects. Each one of the items in each vector layer contains a fixed value for a certain location, it assumes the feature remains constant throughout space. Vector data can be represented by points (simple set of coordinates), lines (continuum of points), or polygons

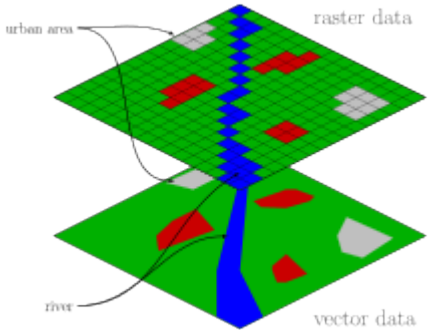
(objects that form a closed area defined by connecting lines). Commonly these are used to represent soil sample locations, stores, cities, roads, streams, or regional boundaries.

- **Raster data**, or continuous objects. Because object values can vary over space (e.g., soil properties), independent locations are included at all locations of the study area. A raster is an image created by a composition of grid-arranged squared cells. Each one of the cells is called a pixel, has a unique absolute location, an individual value, and the same size as all other cells. More pixel density per area increases the level of detail, resulting in smoother images. When pixel size increases, the resolution of the map reduces and gives it a blockier appearance.

The process of obtaining data is either done by directly evaluating the object by touching it or evaluating it from a certain distance. Direct measurements of certain feature are obtained with in-field sensors. In agriculture such measurements can be either from the soil (e.g., moisture readings) or the crop (e.g., chlorophyll-meter). As an alternative, remote sensing allows farmers to obtain data from a distance. This includes images from drones, planes, or satellites, which can measure topography or spectral bands (color). Actually, both are being combined with GIS and artificial intelligence methods to increase the quality of the maps.

## Raster vs. Vector data

Because raster pixels have a square shape, they cannot represent other geometry than that. Therefore, rasters fail to perfectly delineate non-squared objects. Instead, vector objects can delineate any figure better because the main unit is the point and by arranging infinite amounts of points, any shape can be delineated. Vector polygons may provide a better alternative for delineating irregular objects, but they assign a uniform value to the are enclosed within and detail is lost. On the contrary, because rasters can include infinite number of pixels, they are able to capture all the variability that exists within certain area.

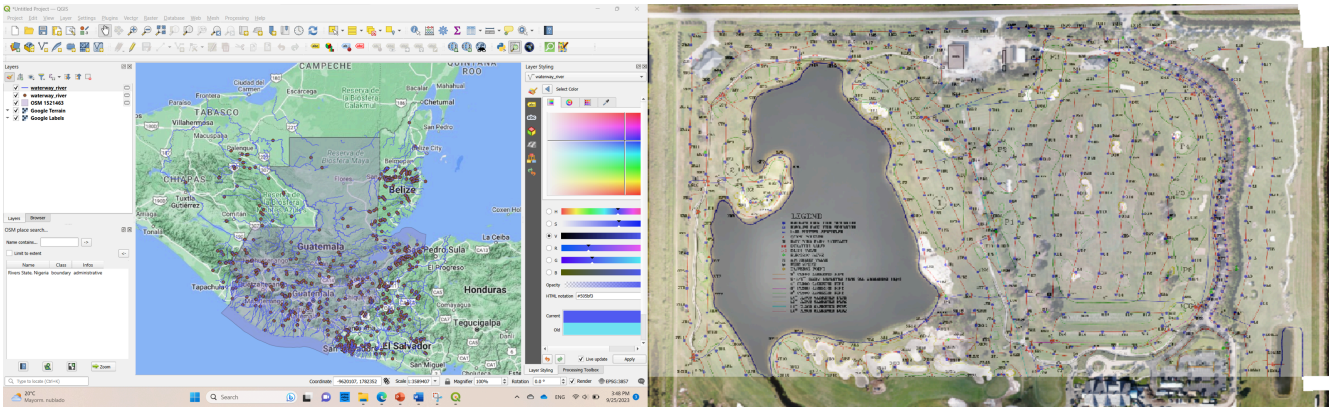



Difference between raster data and vector data for any geographic space. [Image Credit: Johannes Rössel, CC BY SA 3.0]

Soil survey maps that have been digitized are composed of vector objects. Each one of the lines enclosing a certain region assumes that all the area inside is homogeneous. Instead, rasters allow to capture any kind of heterogeneity that exists, especially with dynamic soil properties like nitrogen.

One of the most valuable things about GIS is that scale is no longer a problem. Instead of scale being

limited by the map's extent, in GIS it is possible to zoom in and out of the object and increase the level of detail that can be seen. This does not mean that GIS has better resolution than paper maps. Resolution is still limited by the availability of data and density of it. The difference with paper maps is that to fit a large region within a paper, the level of detail was compressed so intensely that it lost usability, especially with new Precision agriculture technologies. Now, GIS allows the user to zoom in and be able to see that detail that was lost in the transcription to paper maps. Nevertheless, if the smallest unit of sampling represents 1km2, for example, GIS won't be able to see beyond that and all the area will be represented by a big pixel of 1 km2 of resolution.




Examples of GIS technologies. LEFT: screen of QGIS (free access GIS software) where a base topographic map is being used to overlap vector layers of the Guatemalan political boundary and the waterways within the country. RIGHT is a base map created using a drone image to georeferenced an irrigation map for a golf course in Florida [Image Credit: Arturo F.]

## Key Takeaways

- Making spatial predictions is required because it is not possible to sample soil at every location, therefore, soil maps are realistic representations of soil heterogeneity and can involve error.
- Soil spatial patterns may be explained by landscape position associations or by distance to known soil locations.
- GIS integrates software and hardware to boost the mapping process and spatial data analysis.

CHAPTER 16

# Soil Maps around the World

**Bradley Miller and Arturo Flores**

## Learning Objectives

- Compare the difference between soil maps in the United States versus the rest of the world.
- Discuss the available alternatives for the lack of soil maps.

**Keywords:** soil survey, site specific maps,

## Soil maps around the world

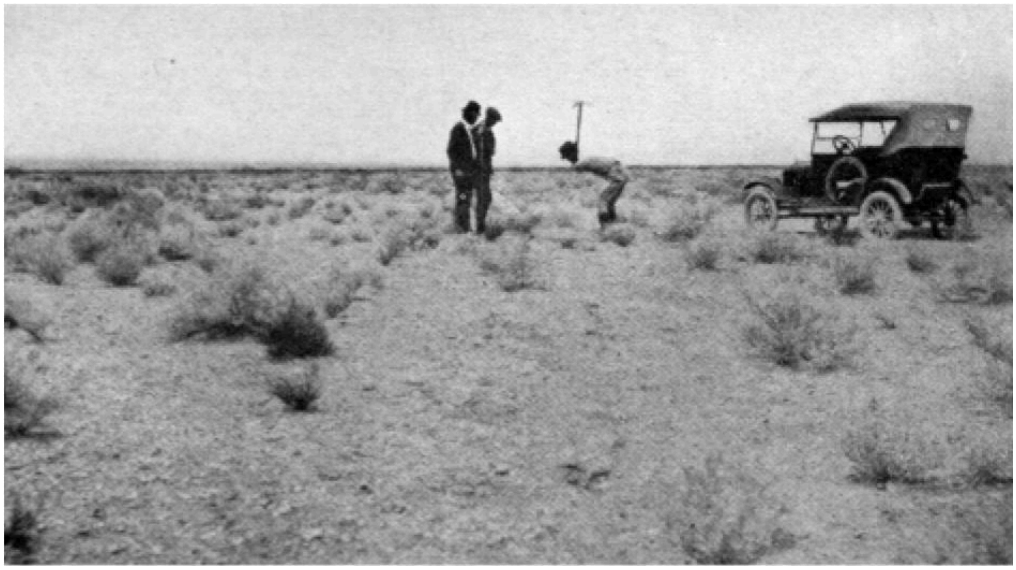
A paradox in public support for soil mapping is that users are increasingly asking for the maps to do more. Then, when the soil maps fall short of those expectations, opinions shift to the soil survey maps not being useful. For example, many farm managers have sought to be more strategic with their sampling for soil fertility by dividing a field into management zones (the core concept of Precision Agriculture). A common approach to identify those management zones is to use the delineations from the soil survey maps. Sometimes this works well, and sometimes the soil survey maps do not include important variations. Note that sub-field management was not included as one of the purposes for soil survey maps.

Given the many purposes of soil maps and the large success of the soil survey program in the USA, many Americans take for granted that they can go online and look at a soil map for around 99% of the land in the USA. Few countries have soil maps with the coverage extent and level of detail provided by the USA soil survey program. At least part of this achievement can be explained by synergistic public investments, such as soil conservation efforts and providing jobs for veterans after major wars/

conflicts. Many countries shut down their soil survey programs during the Farm Crisis of the 1980s.[1] The USA stands out in its continued funding of soil surveys through that time.

## Soil maps in the United States

In 1899 the USA's federal government established the Bureau of Soils to conduct a consistent and coordinated soil survey. Today, the USA soil survey maps include a plethora of interpretations to help translate the knowledge of soil scientists into information needed by landowners to make management decisions. These interpretations can include the suitability for recreational facilities (e.g., campgrounds or golf courses), wildlife habitat, building site development (e.g., basements or streets), sanitation facilities (e.g., septic tanks or landfills), as a construction material (e.g., source of fill dirt or gravel), and water management (e.g., reservoirs or irrigation).



USDA, Soil survey 1923.

One of the early soil surveyors for the USA's Bureau of Soils was Hugh Hammond Bennet. During the soil mapping of Louisa County, Virginia in 1905, he was directed to investigate declining crop yields in the area. He was struck by the differences in the condition of soil under virgin timberland compared to cultivated fields.[2] His advocacy for soil conservation led to him becoming the first director of the Soil Erosion Service in 1933. Although the degradation of soil has always been a challenge for human

1. *The farm crisis of the 1980s*. (n.d.). Iowa PBS. https://www.iowapbs.org/iowapathways/mypath/2422/farm-crisis-1980s

2. Natural Resources Conservation Service. (n.d.). *Hugh Hammond Bennett Biography*. https://www.nrcs.usda.gov/about/history/brief-history-nrcs/hugh-hammond-bennett-biography

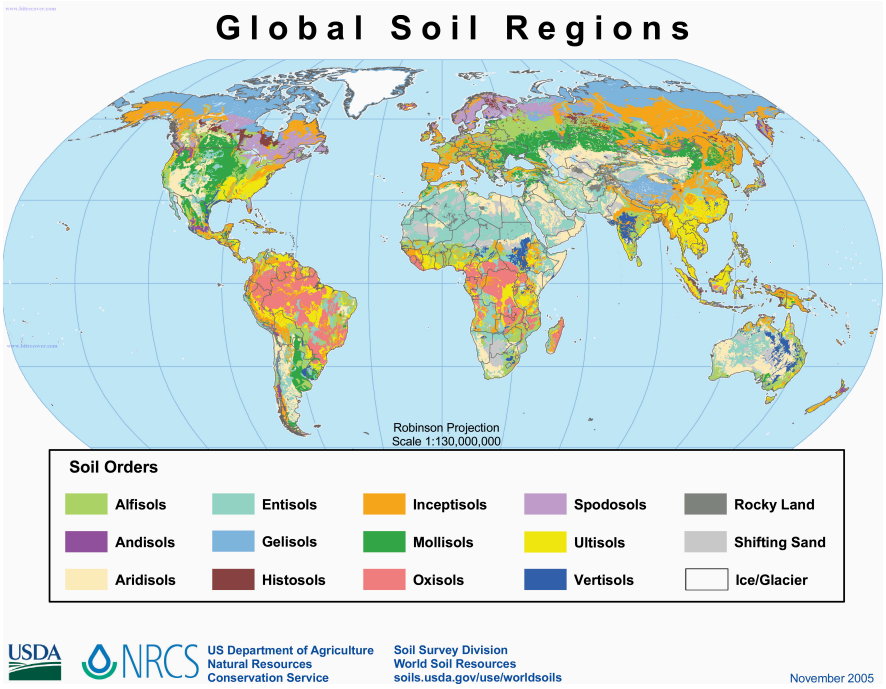
civilizations, the USA experienced a particularly cataclysmic series of events in the 1930s. Coincidently, on the day that Bennet testified before congress in 1935, a dust storm event from the central USA occurred so dramatically that it darkened the sky in Washington D.C. Commonly referred to as the Dust Bowl, the combination of management practices not suited for dryland ecosystems and multiple droughts wiped out tens of thousands of farms. Spurred by the start of the Dust Bowl and investment in public works to stimulate the economy during the Great Depression, Congress elevated the Soil Erosion Service in the USDA and renamed it the Soil Conservation Service. By 1938, the Soil Conservation Service –known today as the Natural Resource Conservation Service – subsumed the Bureau of Soils, making soil conservation the supervisor of soil mapping. While all the previously mentioned needs of a soil survey have remained in place, the lead purpose of soil survey in the USA has been to support soil conservation policy since that time.

Prior to the adoption of aerial photography for soil mapping, most of the maps made by the USA soil survey were made at the county scale. Because of this relatively small extent (large map scale), USA soil survey maps can include more detail. However, until they started using aerial photographs, these maps were more like geologic maps because they could only recognize differences in soil parent material (e.g., bedrock, till, or alluvium) but could not see where different topographic positions occurred in the map. After World War I, aerial photography became more readily available, and the USA soil survey was then able to differentiate landscape positions.

In the USA Midwest, where single season crops were grown, it was possible to have aerial photographs of bare soil. Seeing patterns of lighter and darker soil allowed soil mappers to delineate the tops of hills and the swales between them. This style of soil mapping is called high-low mapping. In areas where there was continuous vegetation cover, the aerial photographs enabled soil mappers to see the type of vegetation growing in different areas and delineate differences in expected soil series based on that. In this way, the level of detail that could be included in a map depended on the map scale, availability of information in base maps, and the purpose of the map.

The USA method of fully utilizing the factors of soil information to associate patterns of soil variation is known as the soil-landscape paradigm. This is a specific example of the geographic concept of spatial association, which is that some variables covary with each other in space. By looking at variables that are more readily observed, one can infer variables that aren't as easily observed. In the case of the soil landscape paradigm, a soil mapper could observe soil properties in one location and infer that other locations with matching climate, vegetation (the part of organisms that can be seen in an aerial photograph), landscape position, and parent material would also have the same combination of soil properties. For example, the Clarion soil series is mapped on the tops of the gentle hills of the Dows geologic formation (region known as the Des Moines Lobe). Within a county scale map, climate doesn't change very much. However, there are measurable differences in climate across multiple counties. For this reason, the Clarion soil series is not associated with exactly the same soil properties from one

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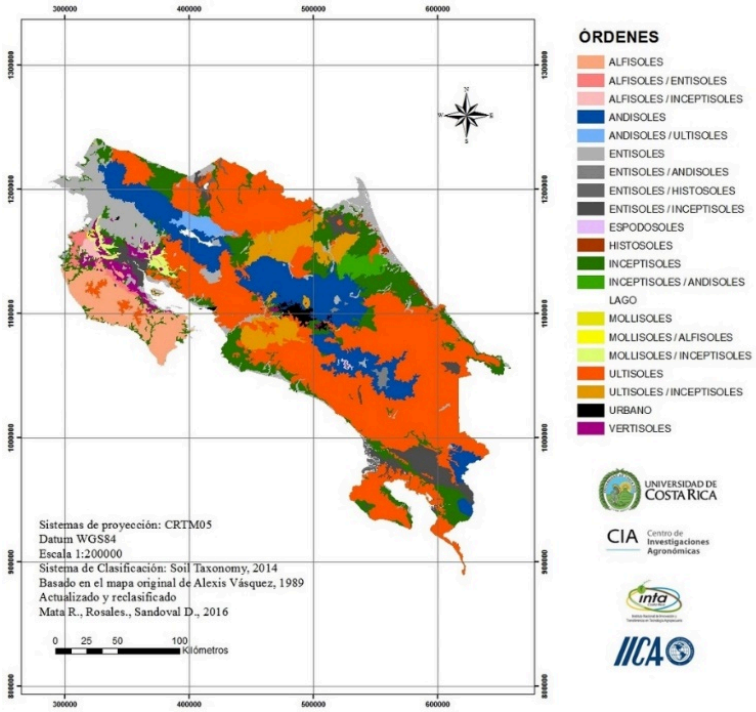

USDA, USDA soil taxonomy global map, marked as public domain, more details on Wikimedia Commons.

## Soil maps elsewhere

The intensive and constant improvements on the USA Soil Maps have produced high-quality and reliable sources of information both for agricultural development and policy making. However, the reality is different outside of the United States. Underdeveloped countries, especially, rely on existent soil classification systems to map their own soils. There is no one concrete reason for the nonexistent efforts on mapping the regions soils in detail as the US has done with their own. Perhaps lack of economic resources, competent politicians, or even disinterest caused by underestimating soil. However, despite the lack of regional soil maps, Central America has thrived and managed soil so efficiently that agriculturally it is one of the most productive regions in the world.

Contrary to the popular use of public available soil maps in the USA, private parties have created their own maps to suit their interests, rather than complying with the national demand. In Guatemala, significant efforts have been made by the sugar cane industry to create reliable soil maps that otherwise are not available. However, these maps have a limited geographic extent, that is, the region

that falls within the sugar cane producing region. Also, because those maps are created with private interests, their accessibility is limited to the general public. Private universities have tried to provide useful data regarding the status of Guatemalan soils, but they are not widely spread and are little known even among farmers. A similar situation occurs in other tropical countries, such as in Honduras and Costa Rica, where banana and pineapple companies invest in their own soil and topography departments to evaluate their land, map their soils, and try to enhance agricultural production. Overall, the private sector efforts are always with the intention of increasing the economic benefit that soil maps can provide. These situations leave small and medium-sized farmers relying on scarce soil maps.




Costa Rica soil map using Soil Taxonomy classification system. Map created by Universidad de Costa Rica Center for Agricultural Research and other institutions.

Soil survey maps provide an overview of the distribution of soil variability; however, they fail to represent fertility parameters and any kind of abnormalities, temporal or permanent, of greater importance mainly for agriculture. This situation puts every farmer in the world at the same starting point: specific soil maps for their land with enough detail to make decisions. Precision agriculture (PA) has slowly gained importance and acceptance among farmers because it relies only on data gathered for that specific field, instead of using regional soil maps. Agriculture is undergoing a paradigm shift in which conventional agriculture is turning into a more data-supported method. Whereas conventional agriculture treats fields as a whole homogeneous unit, PA addresses the local and independent variability that may explain A) soil's fertility, and B) soil's dynamic behavior.

Different technologies are being adopted to practice PA at different scales. Portable equipment, like Veris® technologies (Figure3), that can instantly measure soil pH, EC, and organic carbon by just dragging the equipment once over the field. The most valuable feature of this type of sensors is that the observations are directly transformed into spatial maps. Sugar cane companies in Guanacaste, Costa Rica, are seeing benefits of just tilling compacted soils and doing localized fertilizer applications, as input efficiency increases, and yield is boosted while reducing costs.

The more detailed maps are, the more specific agricultural treatment can be. Conventional sprayers used in pineapple farms are not able to easily adjust their settings once they start working. Drones with individual nozzle control allow adjustments on-the-go depending on treatment maps previously created based on field observations. Dota in Costa Rica is the region of the country known for its coffee production. It is in the mountains and the soil is derived from volcanic materials. Accessibility is limited to machinery and conventional agriculture becomes harder because of the steep topography. Now, drones are being used to evaluate coffee plantations and determine fertilizer requirements based on spectral data captured by the UAV. In Guatemala, sugar cane, pineapple and banana producers use UAVs to also spray fertilizers and pesticides in access-restricted zones, close to urban development's and where planes are not able to reach. A revolutionary company called DISAGRO® works in Latin America and offers PA services that combine meteorology, soil, vegetation, and satellite data to create site-specific management plans. Many other companies and technologies are being developed in the region, demonstrating that the lack of detailed soil maps is not a limiting factor for the region's agricultural success.

## Key Takeaways

- The United States soil maps provide an adequate level of detail to evaluate soil properties and determine management concerns; however, despite their quality and public availability, they are not suitable for site-specific management.

PART V

# Soil Water, Aeration and Temperature

CHAPTER 17

# Soil Water

**Amber Anderson and Arturo Flores**

## Learning Objectives

- Describe where water is held in the soil
- Match water potentials to plant growth conditions
- Discuss factors involved in water movement into and throughout the soil
- Predict how water will move given soil conditions or properties

**Keywords:** soil water potential, plant available water, soil water classification.

## Overview

Water is intrinsically related to soil. It is a crucial resource for life, and an essential component of soil. Soil water is the content of water in an unsaturated system (also, the vadose zone), that is, the soil above the groundwater or the water table. Of particular importance is the nature of water and its interaction with the soil particles.

Water is held in the soil because of hydrogen bonding between water molecules and electronegatively charged soil particles.[1] The water molecules consist of two hydrogen atoms and one oxygen. The way the atoms are arranged causes one side to be more negatively charged than the opposite, creating a polar molecule. The positively charged hydrogens (H+) are attracted to oxygens from other water molecules and/or to oxygens on the surface of the soil minerals and organic matter. Adhesion is the bonding between water molecules and solid particles. Cohesion is the ability of water to bond to other

1. Miller, R.W. & Gardiner, D.T. (1998). *Soils in our environment*. Prentice Hall. 8th edition. ISBN 0136108822.

water molecules. The combination of these forces results in the capillary suction of a soil, which refers to the ability of water to move through the soil pores without the assistance of external forces, that is, in opposition to gravity.

Water flow is directly dependent on the soil texture and its pore distribution. First, water enters the soil by infiltrating through the soil surface, and then it percolates through the profile. For instance, water flow is faster with more granular and sandy soil than when the profile has a platy structure and heavier texture (clay). Several factors may be used to indirectly evaluate the hydraulic conductivity. However, for the purpose of understanding soil water content, the pore space is one of the main driving factors.

Soil porosity is classified according to the size of the individual pores. It is important to remember that water is held in between the soil particles due to the combination of adhesive and cohesive bonds. Capillary pores or micropores are the smallest of the system; mesopores are medium size; and macropores the biggest of all. Well-structured soils have an ideal pore distribution where micropores exist within the soil aggregates and larger pores in between aggregates.[2]

## Water potential

The **water potential** refers to the ability of water to do work and it could be an indirect measure of plant available water. It is measured in kilopascals or bars, and it is commonly expressed with negative value because water held in the soil has limited energy to freely move or react when compared to that of a saturated system (a pool for example). Water movement within the soil is limited by adsorption forces, solute or salt concentration, pressure, and gravity. The **total water potential** considers the effect of the following factors, and plants must overcome this tension to uptake water:

- **Matric potential**: water adsorbed to the surface of soil particles, or the one held in hygroscopic pores, has less potential energy. The matric potential is an indicator of the adsorption or retention force that the soil exerts over water molecules. In a saturated soil it generally has a value of zero. But, in unsaturated soil water is more tightly held and its value becomes more negative as the soil dryness increases. This means that the more negative the value is, or the higher its absolute value, water is less free and more energy is required to make it available. The matric potential is a measure of how hard water needs to be pulled to take it out of the soil system.
- **Osmotic potential**: the concentration of dissolved solutes or salts in the soil restricts the movement of water, especially if there is a membrane like a plant cell through which water must

2. Schoonover, J.E. and Crim, J.F. (2015). An Introduction to Soil Concepts and the Role of Soils in Watershed Management. *Journal of Contemporary Water Research & Education, 154*: 21-47. https://doi.org/10.1111/j.1936-704X.2015.03186.x

pass. It is always negative and its absolute value increases with higher loads of solutes. Plants need an extra load of energy to absorb water high in soluble salts.

- **Pressure potential:** pressurized water is more able to do work. Gasses and overhead water columns put pressure over underlying films of water. This causes water to flow faster and further than in a non-pressurized system. The pressure potential is zero when no additional pressure is applied, and it is positive when the system gets pressurized.
- **Gravitational potential:** refers to the effect of gravity on the energy of water. This is calculated based on the vertical position relative to a reference point. It has a positive value when the water is above the reference plane, and a negative value when it is below. For example, if a water reservoir is located 5 meters above-ground the potential energy will be positive, because it can freely flow downward due to gravity pull. The opposite occurs when water wants to be brought to a higher elevation. In this case, extra energy will be required to make it flow upward, and therefore, the gravitational potential will be negative.

Naturally, water is expected to move in favor of the water potential gradient, that is, from high water-potential (wet) regions to lower water-potential (dry) regions. This gradient indicates that water will flow following the difference in potential between two regions. Equilibrium exists when the water potential is equal throughout the system and there is no more water flowing across it.

In agriculture, water potential needs to be understood to guide irrigation management and achieve successful yields. The most common method to measure it is with a *tensiometer.*[3] This is a device with a ceramic cup on one end that is connected to a water reservoir and a pressure gauge. When it is installed in the soil, water flows from the reservoir to the cup, and then out to the soil to equilibrate the moisture content between the cup and the soil. The pressure gauge measures the suction force applied by the soil to pull water out of the ceramic cup (referred to as tension). This occurs because as soil dries down there are more available charges that pull water stronger and closer to the soil's particles, thus, increasing the matric potential. The tensiometer is not affected by solute concentration, it only measures matric potential. Still, for practical purposes, the matric potential is approximately equal to the total water potential,[4] and this is a relatively inexpensive and simple device to improve water management decisions such as irrigation timing.

3. Ochsner, T.E. (2024). *Rain or shine: An introduction to soil physical properties and processes*. Department of Plant and Soil Sciences, Oklahoma State University.

4. Miller, R.W. & Gardiner, D.T. (1998). *Soils in our environment*. Prentice Hall. 8th edition. ISBN 0136108822.

## Soil water classification: Matric potentials of interest

For practical purposes soil water is classified according to its availability to plants. Soil holds water as films coating soil particles and in the pore space between them. Its availability is directly related to the soil water potential. Water becomes less available when the water potential is higher (more negative values, dry soil), and more available when the water potential is low (less negative, moist soil). In a saturated soil all the pores are filled with water. The water potential at this point is almost zero and it indicates that water flow is not restricted by the matric potential. This occurs after a significant precipitation event and is less dependent on the soil texture. However, the upper horizons do not remain saturated for long and the excess water freely drains away. Drainage takes time and while this happens, plants may used some of this moisture with minimum effort.

First, **saturation** occurs when pores are filled with water (0 kPa). The amount of water held at this potential is equal to the total porosity of the soil. The **gravitational water** is that one that drains downward through macropores due to the force of gravity after soil gets saturated. This is temporarily available for plants, there is a low absolute matric potential affecting, and it takes between 24 to 48 hours for it to become negligible.

After free drainage the soil remains wet but not saturated, and air occupies pore space, especially that of the macropores. At this point, soil is said to have reached field capacity. **Field capacity** is defined as the maximum amount of water that a soil can hold after gravitational drainage.[5] Water is held with a tension of -0.1 to -0.3 bar (-10 to -30 kPa), and plants can easily pull it out of the system.

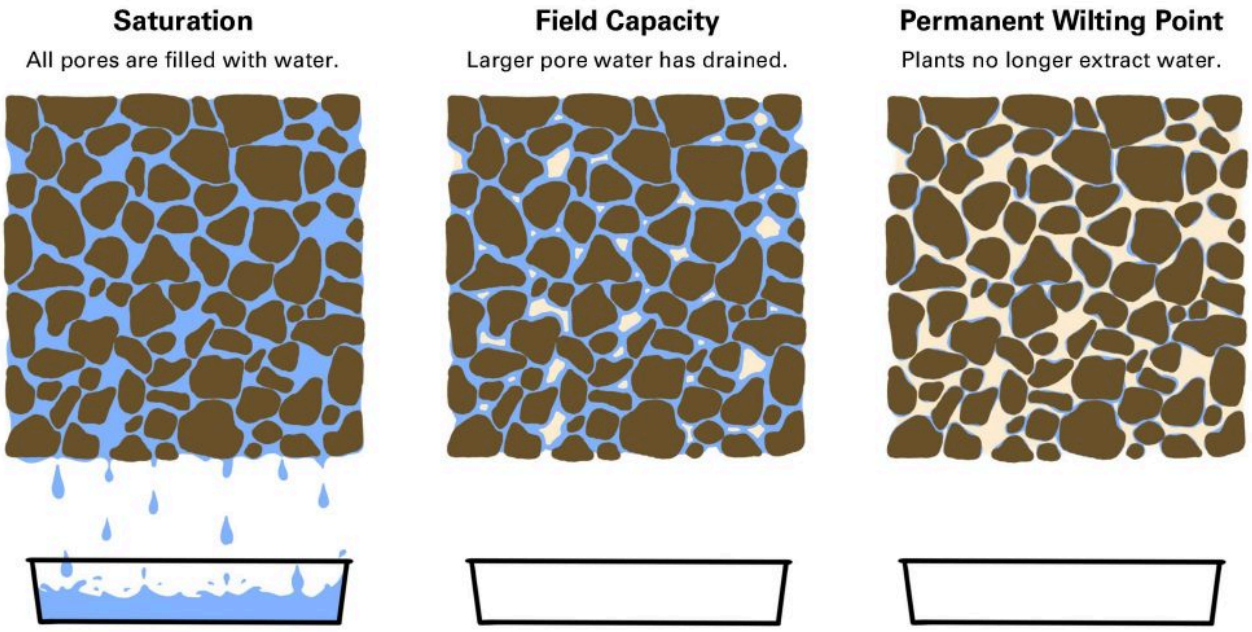
The **permanent wilting point** is reached when water is held with a tension that plants cannot overcome, which is about -15 bar (-1,500 kPa). Plants start to wilt and they may not be able to recover their turgor. A considerable amount of water remains in the soil at this point but is not available for plants. The reason for this is that water is held in the soil's micropores, and it is held with a tension that exceeds the plant's ability to remove it. This is called hygroscopic coefficient (also hygroscopic water within capillary pores) and water is held with a tension close to -31 bar (-3,100 kPa).

The **plant available water** is the moisture content immediately available for plant uptake. Its upper limit is set by the field capacity and the lower limit by the permanent wilting point. Gravitational water is insignificant at field capacity; however, some can still drain but at a much slower rate. Evapotranspiration increases the absolute water potential by reducing the moisture content of the soil and making the remaining less available for plants. To calculate plant-available water, subtract the moisture at field capacity minus the moisture at the permanent wilting point:

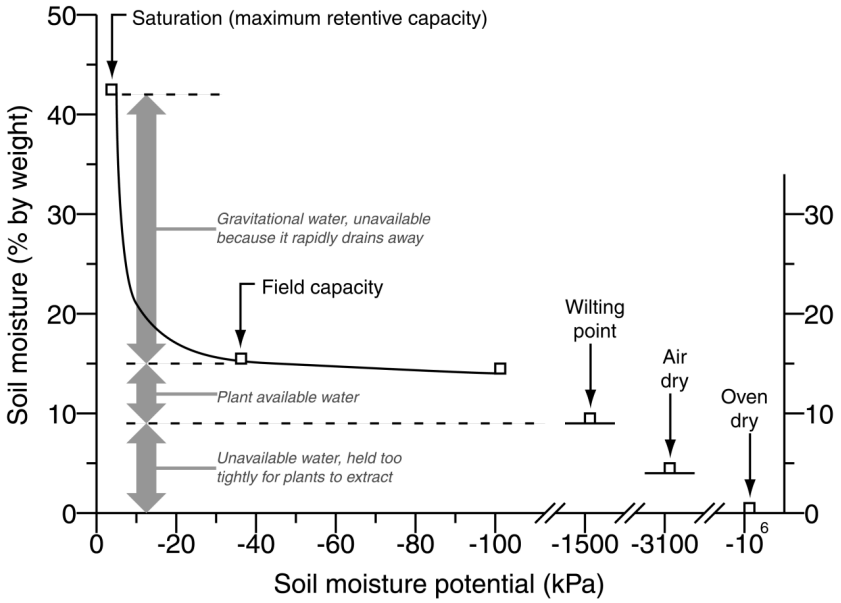
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5. Miller, R.W. & Gardiner, D.T. (1998). *Soils in our environment*. Prentice Hall. 8th edition. ISBN 0136108822.

$$\theta_{PAW} = \theta_{FC} - \theta_{PWP}$$




Three important water potentials of interest. At saturation, all pores are filled with water, and water drains freely from the soil macropores – this is the gravity-drained water. At field capacity, the macropores are empty (containing only air), but the micropores still have water. From here plants take up water, and some also evaporates, until the water films become very thin and only the smallest of micropores still have water. The difference in moisture between field capacity and permanent wilting point is plant-available water. [Image credit: Wyatt Bailey]




Soil moisture curve. [Image Source: Colby Moorberg and David Crouse, 2021, CC BY 4.0]

In practice, plant available water directly depends on the soils texture. Colloidal soil particles (clay and humus) are able to hold more water than sandy soils. In agriculture permanent wilting point should be avoided at all costs to prevent yield reduction. Therefore, soil is allowed to lose only a tolerable percentage of its plant available water before irrigation occurs. This is called **management allowable depletion**. Unlike permanent wilting point that is a set as a function of retention forces, the allowable depletion threshold is set as a function of the crop's tolerance to drought. It is calculated by subtracting a percentage of the plant available water from the field capacity, in terms of tension or volumetric water content. Soil moisture is monitored with soil sensors, like tensiometers, that provide users with an approximation to soil water content. This can be later related to volume of water per volume of bulk soil and help monitor irrigation practices.

## Soil water content

Air- and oven-dried soils are two concepts that may be found in literature. These refer to the process applied to reduce the moisture from a soil sample. The air-dry method consists of exposing the sample to ambient air or to room temperature (20 – 25 °C) to let moisture evaporate. This is similar to what will occur naturally in a soil, which is a function of evapotranspiration and gravitational drainage. A thin film of water still remains in the air-dry soil, but it is not readily available for plant uptake. This indicates the water held with a tension of -31 bar (-3,100 kPa) and may be associated with the permanent wilting point. The oven-dry process puts soil in an oven at a temperature between 100 – 110 °C until weight remains constant. The extra energy applied to evaporate moisture from the sample makes the

remaining water content be held to a tension up to -100 bar (-10,000 kPa). This process is applied to soil samples when further laboratory analysis is desired, such as particle density or nutrient extraction. Extra temperature applied beyond the recommended ones may risk the composition of the sample, altering the soil's mineralogy and organic matter content. This could be a problem if chemical analysis are performed afterwards. Both of these methods are disruptive procedures, do not allow repeatability, and require time and equipment, limiting its applicability for practical purposes (e.g., crop production).

Another way of communicating soil water content is on a mass or volume basis. Direct measurements include gravimetric (θg) and volumetric water content (θv). The gravimetric method measures the mass of water in a given mass of oven-dry soil (g $g^{-1}$). The mass of water is the difference in weight between the soil sample before and after drying it in an oven. The volumetric water instead indicates the volume of water contained in a given volume of dry soil. This is calculated by multiplying the gravimetric water content by the bulk density of the soil, assuming that the water density equals 1 g $cm^{-3}$. It can be expressed as unitless decimals (cm3 $cm^{-3}$), or as a percentage if multiplied by 100. Additionally, the thickness or depth of water in a soil layer is given as the soil water storage. This one is calculated by multiplying the volumetric water content by the depth of the soil layer (e.g., rooting depth).

In agriculture a popular instrument to measure the volumetric water is called TDR (*Time Domain Reflectometry)*. This device sends an electric signal through some metal probes of known length that are inserted into the soil, and measures the speed at which they travel. The time it takes the signal to go back and forth across the probe is proportional to the dielectrical constant of the soil, in wet soil it takes longer than under dry conditions. The process is more complex than what is explained here, but the advantage of these devices over soil-drying methods is that they allow for instantly repeating measurements at the same location without disturbing the surface. In the golf industry TDRs include also electrical conductivity and temperature sensors that increase the level of detail for managers to take more accurate decisions.

## Soil water demonstration

Watch this overview video at: https://youtu.be/m4iHBy5PNY4

### Key Takeaways

- Water is held in the soil as a result of cohesion and adhesion forces.

- The soil water potential indicates the strength or energy required to remove water from the soil, and it is an indirect measurement of water availability.
- Plant available water is the difference between field capacity and permanent wilting point, and it is readily available for plant uptake.
- Water content may be communicated either as gravimetric or volumetric water content.

CHAPTER 18

# Water Flow in Soil

**Rivka Fidel**

## Learning Objectives

- Explain the differences between the 3 types of flow: saturated, unsaturated, and vapor
  - When is each relevant?
  - When is flow fastest?
  - What factors affect water flow rate when soil is saturated?
- Explain how discontinuities in soil texture (stratified soils) affect water flow

**Keywords**: soil water flow, saturated flow, unsaturated flow, vapor flow

## Importance of soil water flow

Understanding types of water flow in soil and the factors affecting them helps us improve water management in various ways including irrigation system management, flood prevention and mitigation, minimizing leakage risks for hazardous wastes, and turfgrass maintenance. Water flow and wise management thereof is therefore integral to managing a wide array of systems, from agroecosystems to waste storage systems and golf courses.

From the previous chapters, we've learned that water flows from high to low water potential. Here we'll learn what affects the rate of flow, and when.

## Types of water flow

The rate of water flow through soil depends on the amount of water in the soil, specifically the water potential and, concurrently, the thickness of water films. Generally, the thicker the water films (and

therefore the higher the water potential), the faster the water flow in units of volume per unit time. We therefore classify soil water flow into 3 types, based on key water potentials: saturated flow, unsaturated flow, and vapor flow.

## Saturated flow

**Saturated flow**, as the name suggests, occurs when soil pores are completely filled with water. In other words, it occurs at saturation, i.e. when the soil matric potential is 0 ($\Psi_m$=0).

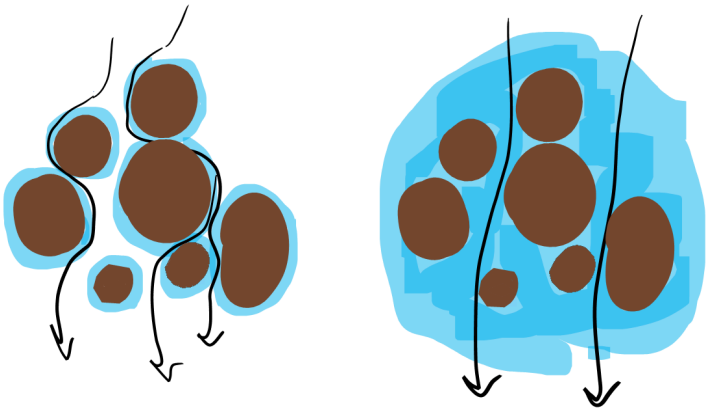
Saturated flow is affected by the same factors that influence permeability: texture, aggregation, and pore connectivity. Use the interactive below to explore the effect of texture.

Increasing aggregation increase the number of macropores found between aggregates (inter-aggregate pores), which, like a larger water pipe, increases permeability and allows for faster water flow. Then, pore connectivity refers to how many pores (especially larger ones) are found directly adjacent to each other so as to form a more direct water flow path through the soil, thereby increasing permeability and water flow rate. We can also think about this in terms of the opposite concept, tortuosity. *Tortuosity* refers to how winding and indirect a path that water (or air) must take to get through the soil. The more tortuous the soil, the longer it takes for water to flow through the soil, resulting in lower permeability, plus slower infiltration and drainage.

The exact rate of saturated flow can be calculated with Darcy's Law, but this is largely beyond the scope of this introductory book. For now, note that flow rate increases with increasing overall permeability (a function of texture, aggregation and pore connectivity as detailed above), and with an increasing difference in water potentials.

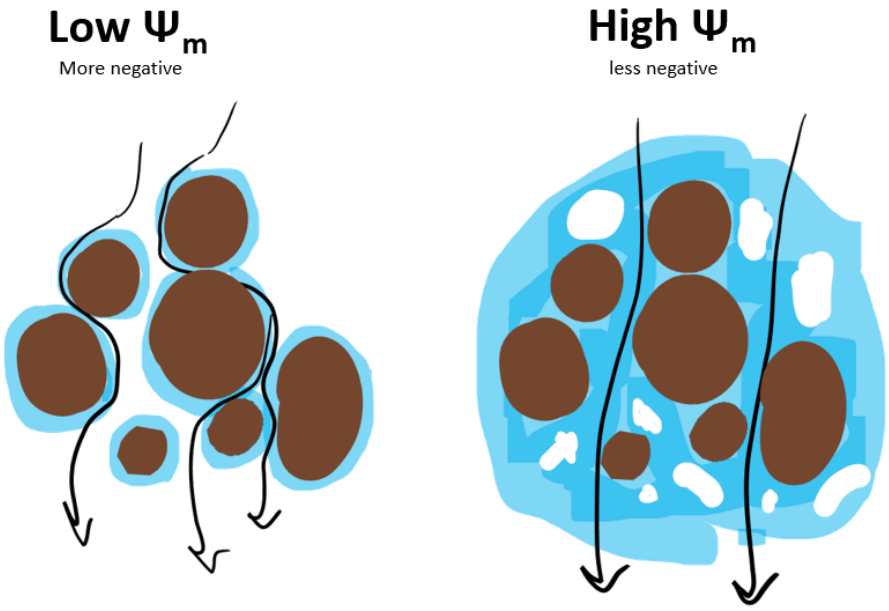
## Unsaturated flow

**Unsaturated flow** occurs after some water has drained from soil, and water moves as a liquid through the remaining water-filled pores and water films. In terms of matric potentials, this occurs between saturation at 0 kPa and the hydroscopic coefficient at -3100 kPa ($-3100 < \Psi_m < 0$). See the vapor flow section for more information on the hydroscopic coefficient.



Unsaturated flow (left) compared with saturated flow (right). [Image credit: Rivka Fidel]

Compared with saturated flow, unsaturated flow is slower because water can only flow through water-filled pores and water films, and therefore must flow around air-filled pores found in unsaturated soils. This increases the water flow path, slowing down water flow. As unsaturated soil dries, the water-filled pores diminish in number and the water films thin, making water flow paths more winding and less direct, slowing down water flow. Therefore, unsaturated flow decreases with decreasing water film thickness. In other words, unsaturated flow is directly correlated with matric potential and water film thickness. The closer the soil gets to saturation, the faster the unsaturated flow.




Water flow at low matric potential (low) compared with water flow at high matric potential (right). [Image credit: Rivka Fidel]

Use the below question to guess the effect of texture on unsaturated flow, and then expand the

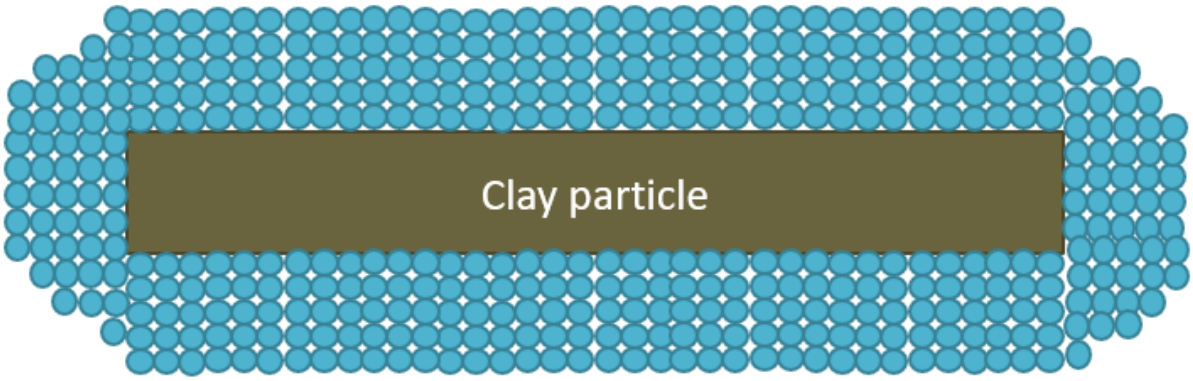
accordion menu below that to learn even more (this concept is intermediate in difficulty and may be optional in introductory courses).

### What is the effect of texture on unsaturated flow?

Interestingly, the effect of texture that we saw in saturated soils applies to unsaturated soils *only when matric potential is high* (>-10 kPa). At low matric potentials (<-30 kPa or so), this trend reverses, and the finer-textured soils begin to have faster flows than the coarser-textured soils. This is because smaller particles have larger surface areas on which to hold water films, and so at lower matric potentials they will have higher moistures compared to large particles, creating a higher density of water films. Therefore, in finer-textured soils, these water films are more connected to each other, creating a more direct flow path.

## Vapor flow

**Vapor flow** occurs when water moves as a gas through the soil, and this becomes the dominant form of water flow when water films are only ~5 or fewer molecules thick. Such thin layers of water occur at or below the **hydroscopic coefficient**, equivalent to a matric potential of -3100 kPa. When water films are so thin, each water molecule is so very strongly attracted to surfaces that it can only break free from the particle surface if it evaporates.




Clay particle with about 5 layers of water molecules adsorbed to it. Each blue circle represents a water molecule. At or below this water film thickness, water needs to evaporate in order to have enough energy to escape its attraction to hydrophilic surfaces like those found on clay minerals, most other silicate minerals, and organic matter. [Image credit: Rivka Fidel]

It is very difficult to measure water potential below -3100, so it becomes easier to predict the direction of vapor flow using humidity. As humidity decreases, water potential decreases. Therefore, water will flow as a vapor from areas of high to low humidity.

Vapor flow is important to desert-adapted plants called *xerophytes*, some of which are capable of taking up water as a gas, frequently by condensing it on contact with the roots. At such low water potentials, soil water content begins to depend more on soil surface area and soil particle surface chemistry. The more surface area available and the more hydrophilic (water-attracting) the surfaces are, the more soil will attract water vapor and the more water it can hold at $\Psi_m < -3100$ kPa.

## Water Flow in Stratified Soils

**Stratified soils** are soils where there is an abrupt change in texture from one layer to the next. For example, when a sand layer is found above a loam layer, or a clay layer is found above a loam layer. Such strongly contrasting textures effectively create a barrier to flow.

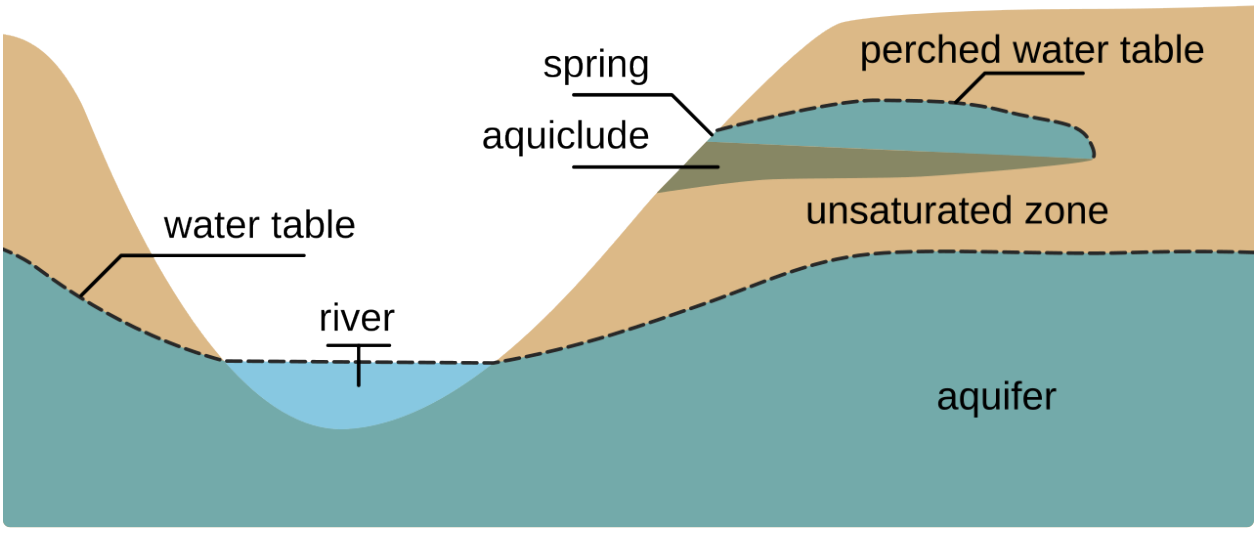
When going from a coarse texture to a fine texture, the water flows quickly down through the coarse-textured layer, then slows and spreads out as it reaches the less permeable fine texture. When going from a fine texture to a coarse texture, the water is attracted to the numerous small micropores in the fine-textured layer, and spreads out in this layer instead of going down to the next layer. Frequently the water will only flow down to the coarser underlying layer after the upper, finer layer is saturated with water. At this point, the water potential in the fine layer is sufficiently high to overcome the effect of texture and allow water to flow down, from high to low water potential.

Check out this video for an example (it also appears in the infiltration and permeability chapter):

Note that in the video, the soil starts off dry so we are primarily viewing unsaturated flow. It is unclear whether any layers temporarily reach saturation as the are wetted.

### Perched water tables and stratified soils

Very stratified soils, with extreme contrasts in textures, can bring water flow to a near-complete halt. This creates what is called an *aquitard*, a relatively impermeable layer. Above this layer, even saturated water cannot flow downwards. This causes groundwater to become "perched," i.e. stuck, above this near-impermeable layer. Such groundwater bodies are called *perched aquifers* or *perched water tables*. Think of the water being perched above the near-impermeable layer, like a bird perched on a tree branch.




Cross section showing the water table varying with surface topography as well as a perched water table. Aquicludes are layers that are impermeable due to the presence of very clayey sediments or solid rock. Perched water tables can form over aquitards (low-permeability layers) or aquicludes (non-permeable layers). [Image credit: Water Table | Jojko.sivek | CC BY-SA 3.0]

In wet regions, a perched water table can create a wetland or other poorly-drained zone. Wetlands have many benefits as explained in subsequent chapters, but the poor drainage would be problematic for growing crops.

In dry regions, a perched water table can be quite boon, as this makes it easier to dig wells and get water when water is scarce. This can even enable formation of ponds and lakes in the desert, making an oasis.




The town of Benson, AZ, rests on a perched aquifer. Notice how the desert appears unusually green because the plants can easily access the higher water table. [Image credit: "Benson, Arizona" | VANKUSO | CC BY-NC-ND 2.0]

One such place is Benson, AZ, where the water table allowed the formation of several ponds and dense growth of vegetation, attracting people to live there as well. Unfortunately this area was contaminated with trichloroethylene (TCE), so the water became unsafe to drink, and hazardously close to the surface as well. In summation, stratified soils and other poorly permeable layers can profoundly change the overall hydrology of an area.

## Key Takeaways

This table summarizes the types of water flow:

| Type of flow | When does it occur? | At what matric potential does it occur? | How fast is it? *(volume per unit time)* | Soil texture effects on flow rate | Other notes |
|---|---|---|---|---|---|
| **Saturated** | All pores filled with water | $\Psi_m$ = 0 kPa | Fastest | Coarser faster | — |
| **Unsaturated** | Some pores have air and some have water | < 0 kPa *(& $\Psi_m \geq$ -3100 kPa)* | Medium | *Depends on* $\Psi_m$<br>**$\Psi_m$>-10 kPa:** faster for coarser-textured soils<br>**$\Psi_m$<-30 kPa:** faster for finer-textured soils | Flow rate increases with increasing $\Psi_m$ |
| **Vapor** | Water held in films 5 or fewer water molecules thick | $\Psi_m$ < -3100 | Slowest | None | Water flows as gas ($H_2O_{(g)}$) |

Abrupt changes in soil texture from one layer to the next, found in **stratified soils**, additionally causes water flow to slow down when one or more layers is unsaturated.

CHAPTER 19

# Infiltration and Permeability

**Amber Anderson**

## Learning Objectives

- Identify factors influencing infiltration and permeability
- Predict how a soil difference, either management or natural, might impact permeability or infiltration rates

**Keywords:** Infiltration, permeability

## Overview from the NRCS

> Watch the video at: https://www.youtube.com/watch?v=vmo0FRAVgkM

As seen in the video or during any rainfall, a raindrop hits the ground with significant force. This force could dislodge the particles, leading to runoff and erosion discussed in the following chapters, or it could enter (infiltrate) and move through the soil (soil permeability or hydraulic conductivity).

Infiltration and percolation are two concepts that describe the rate at which water moves into the soil (infiltration) and through the soil profile, vertically and horizontally (percolation). And permeability explains how well water can move through the porous media or the soil.

## Water movement in soil

This video shows water movement in soil with contrasting particles or other changing scenarios.

Watch the video at: https://www.youtube.com/watch?v=ego2FkuQwxc

### Check it out!

- You can measure infiltration in your own field or yard using this method [PDF][1]
- Check out more information about infiltration here [PDF][2]

Watch this overview video at: https://youtu.be/XSOWxaW4JG8

1. Natural Resources Conservation Service. (n.d.). *Infiltration—Soil Health Guide*. https://www.nrcs.usda.gov/sites/default/files/2022-11/Infiltration%20-%20Soil%20Health%20Guide_0.pdf
2. Natural Resources Conservation Service. (n.d.). *Soil Quality Indicators*. https://www.nrcs.usda.gov/sites/default/files/2022-10/Infiltration.pdf

## Examples

**Capillary movement** is the water movement through the soil profile thanks to adhesivity and cohesion forces. Adhesion forces allow water molecules to stick together, and cohesion describe the attraction force that bonds water to other surrounding particles different from water (eg., soil particles). Based in this principle, PC-Drainage (passive capillary drainage) is a modern technology being implemented in golf courses.

As the picture shows, rope is buried underground all around the main basin. This rope is porous material with a hollow stainless-steel mesh core that transports water to the basin. When the rope is installed, a layer of sand is poured on top, this creates a different texture barrier that makes water percolate deeper faster than laterally, increasing the water captured by the rope. This method is widely used in golf courses because its installation does not require digging deep trenches for conventional pipe, allowing golfers to play right after its installation. Also, the porous media replaces the conventional tile drainage that is easily clogged with fine soil particles, like silt.



Passive Capillary drainage in a saturated soil in Florida. [Photo Credit: Arturo Flores]

## Key Takeaways

- Texture, structure, residue, and crusting influence infiltration or how water move into a soil
- Texture, structure, contrasting particle sizes influence permeability or how water moves through a soil

CHAPTER 20

# Soil Aeration

**Rivka Fidel**

## Learning Objectives

- Define: aeration, air-filled porosity, mass flow, and diffusion
- Explain the main factors affecting aeration
- Explain how aeration influences important soil processes relevant to soil formation and plant growth

**Keywords**: aeration, porosity, respiration

## What is aeration?

**Aeration** is the degree of mixing of soil air with atmospheric air. Much like the air feels fresher in your home with all of the windows wide open, the faster the air moves into and out of the soil, the better aerated the soil is. The better the soil aeration, the more oxygen will be in the soil.

Aeration can be measured 3 ways:

- **Percent oxygen:** calculate the $\%O_2$ in the soil, or the ratio of $O_2$:$CO_2$. A higher $\%O_2$ or higher $O_2$:$CO_2$ ratio signifies better aeration.
- **Air-filled porosity**: This is the percentage of soil pores that are filled with air, out of the total pores. The greater the air-filled porosity, the greater the aeration. Air-filled porosity can be calculated as:

$$AFP = TP - \theta_v$$

Where:
***AFP*** = air-filled porosity
***TP*** = total porosity
$\boldsymbol{\theta_v}$ = volumetric water content = water-filled porosity

- **Redox potential ($E_h$):** a measure of how easily chemicals can acquire or lose electrons; proportional to the amount of energy redox reactions will yield given the chemical species present.[1] Learn more about this in the Redox Processes and Wetlands chapters. *(This concept is frequently considered intermediate instead of introductory, it so may be optional in introductory soil science courses.)*

## Example Air-Filled Porosity Calculation

Consider a soil with a volumetric moisture of 25% and a bulk density of 1.3g/cm$^3$. To calculate air-filled porosity, we first need to calculate total porosity:

$porosity = TP = 1 - D_b/D_p$

$= 1 - 1.3\ g/cm^3 \div 2.65\ g/cm^3$

$= 1 - 0.46$

$= 0.54$

Now, we can plug the total porosity into the air-filled porosity formula:

$AFP = TP - \theta_v$

$= 0.54 - 0.25$

$= 0.29$

$=$**29%**

This can alternatively be done entirely with percents:

1. Wang, J., Wood, J., Lee, E., & Brar, L. (2023). Standard reduction potential. In *Electrochemistry*. Chemistry LibreTexts. https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Supplemental_Modules_(Analytical_Chemistry)/Electrochemistry/Redox_Chemistry/Standard_Reduction_Potential

$$\%AFP = \%TP - \%\theta_v$$

$$=54\% - 25\%$$

$$= \mathbf{29\%}$$

## Importance of aeration

Aeration is integral to plant root growth and affects numerous soil processes. Plant roots require oxygen to perform aerobic respiration (i.e. to "breathe") and so over time, plants without sufficient root aeration will suffocate and die.

Like plant roots, aerobic microbes need oxygen gas ($O_2$) to perform aerobic respiration. When aeration is slow, therefore, microbes tend to grow more slowly, leading to slower organic matter decomposition. Furthermore, when aerobic microbes run out of oxygen, their growth stops, and other microbes that use other compounds for respiration begin to grow instead. These microbes frequently use plant nutrients and important components of soil minerals, and/or produce greenhouse gas emissions. Hence, aeration also affects soil nutrient content, mineral composition, and soil greenhouse gas emissions. Abiotic reactions are also affected by the presence or absence of oxygen. Therefore, due to both biotic and abiotic processes, soil development fundamentally changes when aeration changes.

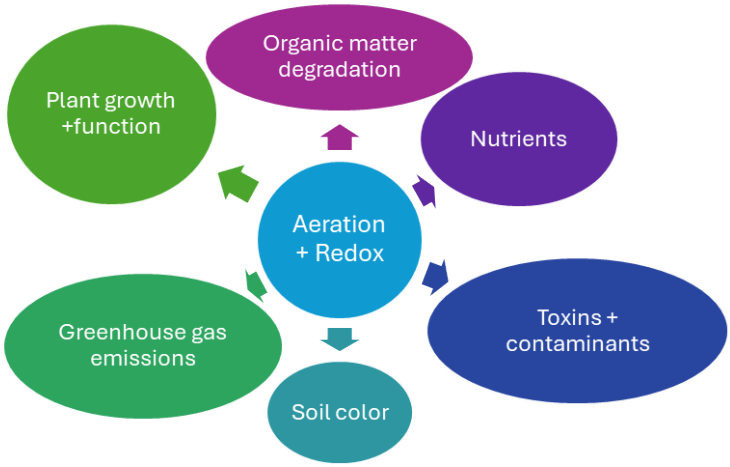



Diagram showing that aeration and redox processes influence soil properties and processes. [Image Credit: Rivka Fidel]

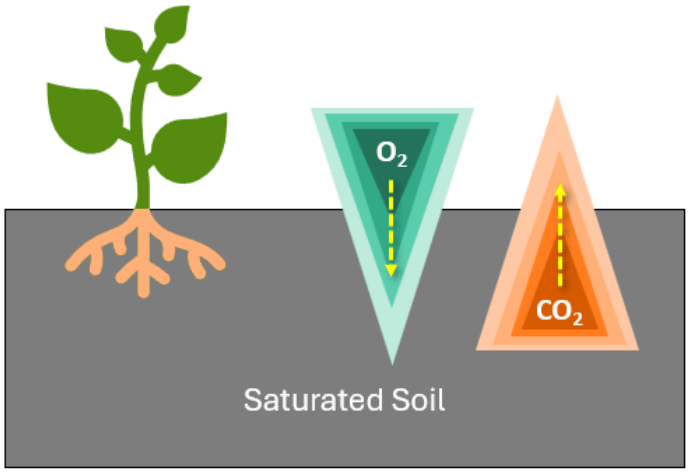
## How aeration works

What causes air to flow in and out of soil? It comes down to the two ways that gases can move: mass flow and diffusion.

**Mass flow** is the bulk movement of fluids and solutes (including gases) from high to low pressure, i.e. movement along a *pressure gradient*. A pleasant breeze or water flowing in a stream are both examples of mass flow, even if you can't sense the pressure difference. You've also observed mass flow if you've ever let air out of a balloon: the air in the balloon has a higher pressure than outside the balloon, so when you open up the balloon or pop it, the air exits the balloon via mass flow, from high to low pressure. In soil, both soil particles and water-filled pores block the mass flow of gases.

**Diffusion**, by contrast, is the movement of a specific solute – including gases – from areas of high to low concentration (movement along a *concentration gradient*). Typically the atmosphere has a greater oxygen concentration than the soil, so oxygen diffuses from the air to the soil. Diffusion is much slower than mass flow. *Diffusion of dissolved $O_2$ gas is additionally 10,000x slower through water than through air!*

Because water impedes the flow of $O_2$ and other gases so drastically, increasing moisture dramatically reduces aeration.

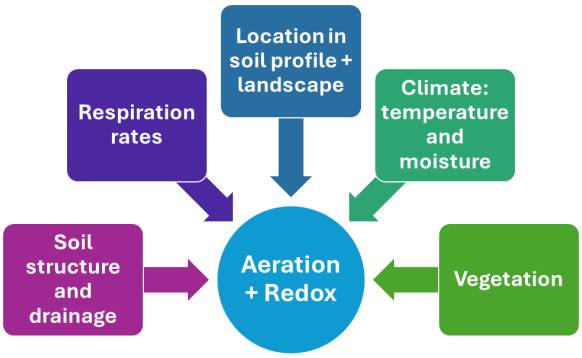



Because soil has higher concentrations of CO2 and lower concentrations of O2 compared with the atmosphere, there is generally a net flux of CO2 exiting the soil, and a net flux of O2 entering the soil. The contrast between atmospheric and soil concentrations is even greater in saturated soils, but these soils also experience much slower gas flow (both by mass flow and diffusion). [Image Credit: Rivka Fidel]

## Factors affecting aeration

Based on how the flow of $O_2$ gas works, and our understanding of what organisms use $O_2$ gas, we can

predict what factors will affect aeration, whether it's measured as air-filled porosity or $O_2$ concentration. These factors are all related to soil structure, soil moisture, and/or soil organisms.




Conceptual illustration of the factors affecting soil aeration and redox processes. See the wetlands chapter for more on redox reactions and their effects. [Image credit: Rivka Fidel]

## Soil structure and drainage

Any aspect of soil structure that improves soil drainage will also improve soil aeration, because the faster water flows out of the soil, the faster the water-filled pores empty out, making room for air and increasing the air-filled porosity. Air, then, can flow through the air-filled pores, increasing aeration.

Here is a brief summary of soil physical properties affecting aeration (these are very much interrelated with each other):

- **Texture**: *Other factors remaining equal (especially aggregation),* smaller particles will have smaller pores between them, slowing the flow of water and drainage, and reducing aeration.
- **Aggregation**: better aggregation increases macroporosity, increasing drainage and aeration.*
- **Porosity**: greater macroporosity leads to better drainage and aeration
- **Tortuosity**: the more winding (less direct) the flow path for air or water, the slower the drainage and the poorer the aeration. Conversely, more direct flow paths created by better macropore connectivity enhance drainage and aeration.
- **Soil structure type**: Some structures, such as platy structures, have very high tortuosity and hence lower aeration. However, other structures such as granular structures, have low tortuosity and better aeration. More in the infiltration and drainage chapter.

**Inside* an aggregate, aeration decreases as you approach the center of the aggregate. However, aggregation still increases soil aeration as a whole due to how macroporosity aids both air and water flow.

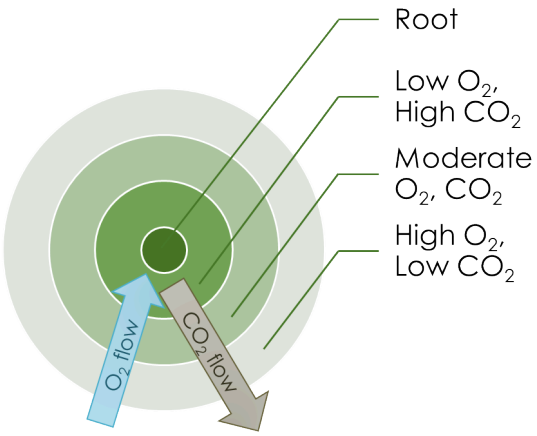
## Organism respiration rates

As mentioned earlier, both plant roots and aerobic microorganisms perform aerobic respiration. To review, the reaction for aerobic respiration is:

$$C_6H_{12}O_6 + 6O_2 \leftrightarrow 6CO_2 + 6H_2O$$

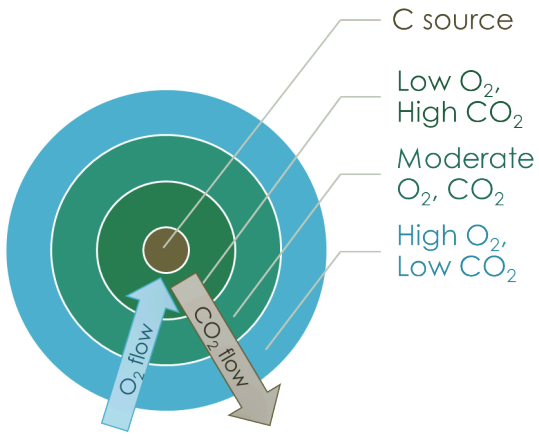
As you can see, the reaction has $O_2$ gas in the reactants and $CO_2$ gas in the products. Consequently, aerobic respiration leads to lower aeration. This is why soil has lower $O_2$ and higher $CO_2$ than the atmosphere, and why mixing atmospheric air with soil air increases aeration.

### Root respiration




In plants, photosynthesis occurs in the leaves and respiration occurs everywhere, but mainly in the roots. As a result, as proximity to a root increases, $O_2$ concentration decreases and $CO_2$ concentration increases. Because gases diffuse from areas of high to low concentration (and move through mass flow from high to low partial pressure), the $O_2$ gas will consequently flow towards the roots, and the CO2 will flow away from the roots. [Image Credit: Rivka Fidel]

### Microbial respiration




As with plant roots, aerobic microbes consume $O_2$ and produce $CO_2$ through aerobic respiration. However, they're found everywhere in soil, so the question becomes: where are microbes most abundant? Microbes need substrates such as dead plants or animals to provide a carbon source, so microbes achieve the greatest densities close to these substrates. So as proximity to, say, buried leaves or animal droppings increases, $O_2$ decreases and $CO_2$ increases. Like with roots, $O_2$ will consequently flow or diffuse towards the zone of dense microbes, and $CO_2$ will flow or diffuse away. [Image Credit: Rivka Fidel]

Consequently, anywhere near soil roots or large concentrations of aerobic soil microbes will have lower aeration.

## Location in the soil profile and landscape

Within a soil profile, aeration normally decreases with increasing depth. This is simply because the farther away the point of interest is from the surface, the further air has to travel to get there. The effect

of soil depth is compounded by moisture and structure – so aeration will decrease with increasing depth much faster in a soil with poor aggregation, low microporosity, and/or poor drainage.

Regarding landscape position, you may recall from the soil formation factors that topography plays a major role in influencing clay content. Going downslope, clay content tends to increase because a) clay erodes downhill, and moves between larger particles downhill, and b) soil at the bottom of the hill receives more water from uphill, causing it to weather into smaller particles (like clay) faster. Given that increasing clay content decreases drainage and aeration, we would expect aeration to also decrease as we go downslope (i.e. as elevation decreases within a landscape). So, we'd expect to find the poorest aeration on toeslopes and in closed depressions.

Lastly, the position of the groundwater table interacts with the effect of both location within a soil profile and the landscape to affect aeration. As you go down within a soil profile, you get closer to the groundwater, so soil moisture increases and aeration decreases. Going downhill also brings you closer to the groundwater – which, as you may recall, is saturated with water, and alternatively called the "saturated zone" – thereby decreasing aeration as well. At the bottom of a hill, where the groundwater is close to the surface, aeration decreases the most rapidly with increasing soil depth.

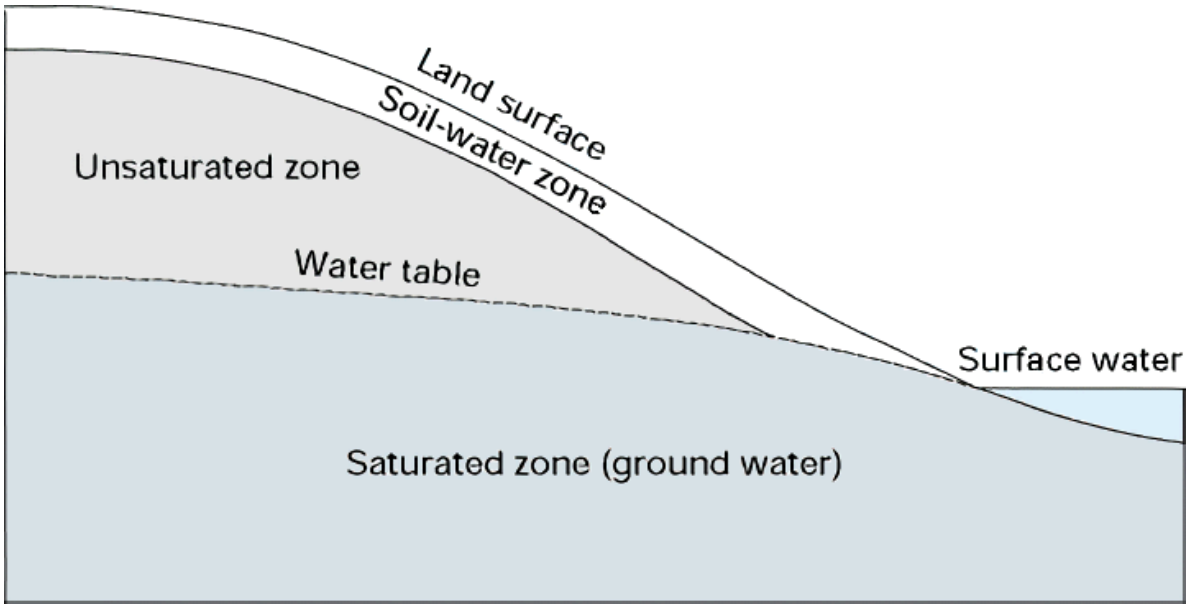



Diagram showing how the water table gets closer to the soil surface as you go downhill, decreasing soil aeration. [Source: USGS circular 1139, Box A]

## Climate

Comparing soil aeration between regions, both average precipitation and temperature, and their variation across seasons, affect soil aeration.

### Precipitation

Areas with higher precipitation, and hence soil moisture, experience lower aeration on average. Not only do soils in wetter regions receive more water at the surface, but also usually have higher water tables on average. Given that water flows from high to low water potential, and the matric potential of the saturated zone (groundwater) is zero, this higher water table reduces drainage. All other factors remaining the same, aeration and precipitation are therefore inversely related.

### Temperature

Temperature has two contrasting effects. First, an increase in temperature leads to an increase in evaporation, leading to decreased soil moisture and increased aeration. Second, when controlling for moisture (i.e. when effects on evaporation are negligible) and other factors, increasing soil temperature increases microbial respiration, and this decreases aeration.

## Vegetation density and transpiration

Unlike proximity to roots, increasing density of vegetation at the landscape scale actually increases aeration. This occurs because as plants transpire, they decrease soil moisture and lower the groundwater table, thereby increasing air-filled porosity and drainage.

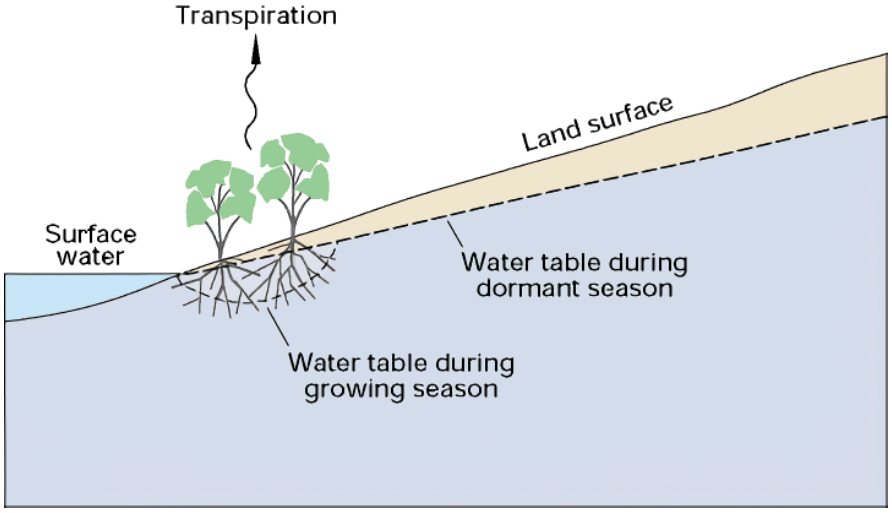



Diagram showing how the dense vegetation such as a stand of trees increases transpiration and lowers the water table. [Source: USGS circular 1139, Hydrologic Cycle and Interactions]

## Key Takeaways

- **Soil aeration** is the degree of mixing between atmospheric air and soil air. It can be measured 3 ways:
    - **Percent oxygen:** calculate the $\%O_2$ in the soil, or the ratio of $O_2$:$CO_2$. A higher $\%O_2$ or higher $O_2$:$CO_2$ ratio signifies better aeration.
    - **Air-filled porosity**: This is the percentage of soil pores that are filled with air, out of the total pores.
        - The greater the air-filled porosity, the greater the aeration.
        - Air-filled porosity can be calculated as $AFP = TP - \theta_v$
    - **Redox potential ($E_h$):** a measure of how easily chemicals can acquire or lose electrons
- Aeration is important because plant roots need oxygen and aeration affects countless redox processes in soil that in turn affect numerous soil properties including nutrient concentrations, greenhouse gas emissions, and even soil color.
- Factors affecting aeration
    - Soil texture, structure and drainage
        - Finer texture → slower drainage and air flow → ↓aeration
        - Better structure → ↑macroporosity and drainage → ↑aeration
        - Better drainage → better aeration
    - Respiration rates
        - More respiration → ↑$CO_2$ and ↑$O_2$ → ↓aeration
        - Denser roots → ↑respiration → ↓aeration
        - Denser substrates (microbe "food") → Denser microbes → ↑respiration → ↓aeration
    - Location in soil profile + landscape
        - Lower in soil profile → usually ↓aeration
        - Lower in landscape → ↓aeration
    - Climate: precipitation and temperature
        - ↑precipitation → ↓aeration

        - Hotter → ↑evapotranspiration → ↓moisture → ↑aeration
        - Hotter (with equal moisture) → More respiration → ↑$CO_2$ and ↑$O_2$ → ↓aeration
    - Vegetation density and transpiration
        - ↑plant density at the landscape scale → ↑transpiration → ↓ soil moisture → ↑aeration

CHAPTER 21

# Soil Redox Processes

**Rivka Fidel**

## Learning Objectives

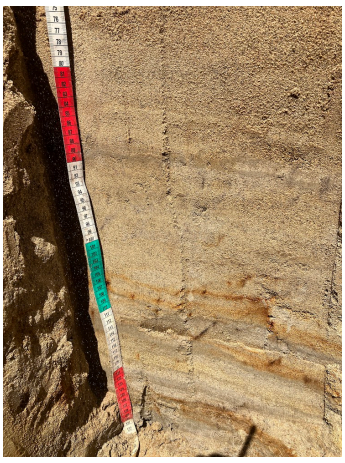
- Identify features of reduction-oxidation processes in soil
- Explain significance of redox features
- Predict the order in which microbes will use different oxidizing agents based on the redox ladder

**Keywords**: redox process, oxidation, aerobic microorganisms

## Importance of the Soil Redox Process

Reduction and oxidation (redox) reactions affect numerous soil processes, ultimately influencing nutrient availability and mobility, microbial activity, soil pH, and even soil color.

Redox processes alter soil's appearance in ways that help us interpret soil formation conditions. Reduction and oxidation features (redox features, or redoximorphic features) are indicators of important soil conditions, particularly oxygen status. Even in drought conditions, soil redox features can be used to avoid potentially costly issues, like basement or septic system placement in an area with regularly saturated conditions.



Redox features resulting from differential water movement in contrasting soil textures

## Redox Reaction Basics

**Reductionreactions**

occur when an element gains electrons from another element, reducing their charge (making the charge more negative). **Oxidation reactions** occur when an element loses electrons. To help you remember, you can use the mnemonic "*LEO the lion says GER*", standing for:

- LEO: **L**oss of **E**lectrons is **O**xidation
- GER: **G**ain of **E**lectrons is **R**eduction

### Redox Concepts from Intro Chem

Soil scientists apply redox concepts from chemistry to help understand and predict redox processes in soils. Here are some videos explaining redox reactions and how to interpret them at an introductory level (not specific to soil science):

Note that you would not expect to find many of the chemicals in these videos, like F2 or Mg0, in soil.

Some of the most common elements to undergo redox reactions in soil are iron (Fe) and manganese (Mn). They tend to lose their electrons to elements like O in oxygen gas ($O_2$) and N in nitrate ($NO_3^-$).

Both O and N – nonmetal elements that frequently gain electrons, and become "reduced" – are what's called **oxidizing agents**, because they help oxidize other elements. Of these, oxygen is the best oxidizing agent found in nature. That is why organisms that use oxygen for respiration are so common.

Metals like Fe and Mn, however, tend to act as **reducing agents**, because they help reduce the O and N.

## Example Redox Reactions

You may have wondered why metals rust, or why you can't find tiny bits of iron or copper ore lying around in the soil. "Rusting" phenomena are redox reactions! For example, the iron found in iron ore and cast iron pots is $Fe^0$. $Fe^0$ readily donates electrons, as shown in this half reaction:

$$Fe^0 \leftrightarrow Fe^{2+} + 2e^-$$

Notice how the $Fe^0$ gave up 2 electrons, which appear in the products. In giving up electrons, the Fe was **oxidized**, and developed a 2+ charge. Fe2+ can precipitate with OH- and form green rusts. Or, it can react again, like this:

$$Fe^{2+} \leftrightarrow Fe^{3+} + e-$$

Now, you may be wondering where these electrons are going. In nature, oxidation reactions are always paired with reduction reactions, because the electrons must always go somewhere. Half reactions only show half the story! In well-aerated soils, the most common oxidizing agent is $O_2$ gas. It is reduced via this half reaction:

$$O_2 + 4e- \leftrightarrow 2O^{2-}$$

Here, the two oxygens in oxygen gas have accepted 2 electrons each, for a total of 4 electrons.

If we double the first half reaction with iron, and then add it to the one with oxygen, we can write a balanced reaction like this:

$$2Fe^0 + O_2 \leftrightarrow Fe^{2+} + O^{2-}$$

The iron has donated 2 electrons per atom, or 4 total, to the oxygen gas. The oxygen gas develops a -2 charge, and the iron develops a +2 charge. Then, in the presence of water, Fe reacts with water to form green rust:

$$Fe^{2+} + 2H_2O \leftrightarrow Fe(OH)_2$$

Any $Fe^{2+}$ in solution can alternatively react again with oxygen like this:

$$2Fe^{2+} + O_2 + \leftrightarrow Fe^{3+} + 2O^{2-}$$

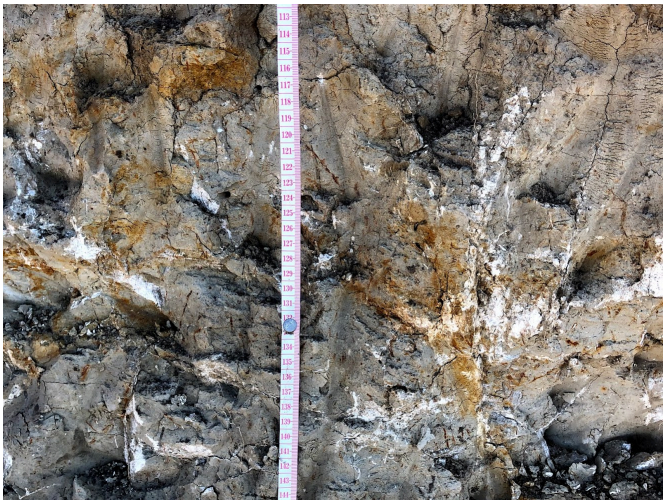
## Reduction Features

Reduced conditions, shown by the grey colors, indicate a lack of oxygen in that soil area. This is frequently associated with saturated conditions, but additional factors can contribute. Even during a drought, redox colors developed due to regular saturation will still be present, making soil color an important indicator of expected wetness conditions.

Reduced iron is mobile, meaning it can move in the soil solution until it comes in contact with oxygen. Other elements such as nitrogen, manganese, and sulfur can also become reduced. These elements are considered “redox active”.



Gleyed soil conditions, found in a sandy soil low on the landscape. Colors began changing to less blue when pulled out of the soil. [Photo Credit: Amber Anderson]



Soil showing redox concentrations (red), depletions (grey), and carbonate accumulations (white) [Photo Credit: Amber Anderson]

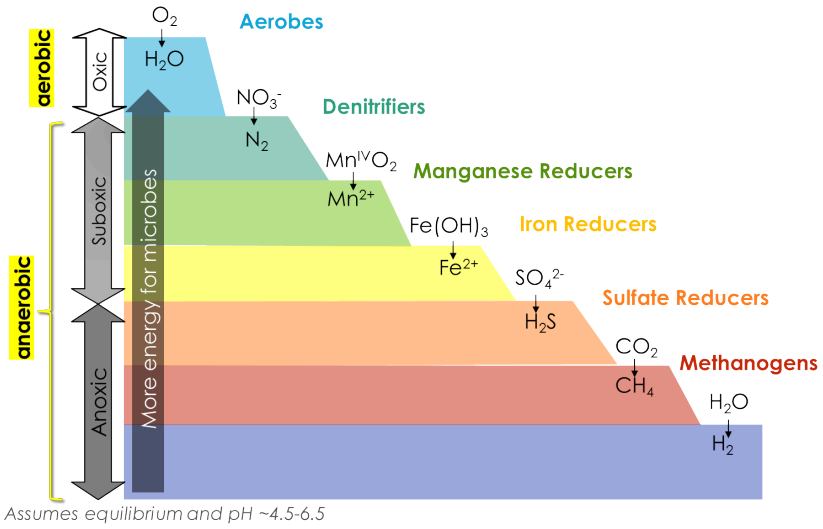
## Changes in Redox Reactions after Flooding: The Redox Ladder

To understand how wetlands function, and how flooding affects non-wetland soils, we need to examine microbes that grow in saturated (waterlogged) conditions and how they respire. All respiration reactions require an **electron acceptor**, a compound or element also known as an oxidizing agent that can accept electrons at the end of the electron transport chain. Thus far we've only discussed **aerobes**, or **aerobic microorganisms** that use $O_2$ for respiration. However, following flooding, aerobes quickly use up dissolved $O_2$. Some microorganisms can only use $O_2$ (obligate aerobes), and these quickly die – but other microorganisms called **anaerobes** can use other electron acceptors (oxidizing agents) such as $NO_3^-$.

However, these alternative electron acceptors come with a drawback: they do not yield as much energy as oxygen. When we arrange common electron acceptors from those that yield the most energy to ones that yield the least, we end up with a diagram called a **redox ladder**, shown below. Each stair step of the redox ladder represents a half reaction performed by different microbes (mostly bacteria and archaea). On the top of each stair step is reactant, so the electron acceptor prior to accepting electron(s), aka the element in it's "oxidized form"; on the bottom of each stair step is the product, including the same element after accepting electrons, aka the element in its "reduced form."

As you go down the redox ladder, each respiration reaction yields less energy. For example, the first step shows $O_2$, the most effective electron acceptor, on the top. On the bottom of the stair step is $H_2O$, which includes $O^{2-}$. This denotes that $O^0$ in $O_2$ gained was reduced to $O^{2-}$ in $H_2O$ because it gained 2 electrons. On the next step, $NO_3^-$ is on the top of the stair step, and $N_2$ is on the bottom. This means that the $N^{5+}$ in $NO_3^-$ accepted electrons, and was reduced to $N^0$ in $N_2$. Because $NO_3^-$ appears below $O_2$, we know that using it as an electron acceptor yields less energy.

Because of the decline in energy yield going down the redox ladder, the microbes performing each successive step in the redox ladder grow slower than those above. So, aerobes grow the fastest, then denitrifiers (a type of $NO_3^-$-reducers), then manganese reducers, iron reducers, and so forth. This is why the microbial community collectively will use the best electron acceptor available, i.e. the oxidizing agent listed highest in the ladder. More about these and other soil microbes can be found in Part X on Soil Biology.




This redox ladder diagram illustrates the progression of microbes and the oxidizing agents (electron acceptors) that they use for respiration, in order of decreasing energy yielded.

In the graphic above, the top of each step on the ladder shows the oxidizing agents prior to accepting electrons ("oxidized forms"), and the bottom of each stair step shows the same compounds after accepting electrons ("reduced forms"). For example, $Mn^{4+}$ in $MnO_2$ at the top of the 3rd step is the 3rd best oxidizing agent in the ladder, and when it accepts 2 electrons, it becomes $Mn^{2+}$, found at the bottom of the same step. This reduction half-reaction is performed by microbes called *manganese reducers*, as indicated by the label to the right of the stair step. Also notice that the soil is considered *aerobic* (or *oxic*) when sufficient $O_2$ gas is available for respiration, and when this $O_2$ runs out, the soil becomes *anaerobic*. Among *anaerobic* conditions, we can further divide the soil status into *suboxic* and then *anoxic* depending on which oxidizing agents are available.

## Why do different electron acceptors yield different amounts of energy?

You might be wondering why exactly the different electron acceptors (oxidizing agents) in the redox ladder yield different amounts of energy, and why this decreases going down the ladder. It comes down to two concepts from chemistry: redox potential and Gibbs Free Energy (these concepts are frequently optional in introductory soil science courses). **Redox potential** (Eh) represents the tendency or ease with which electrons transfer in a given chemical environment. It is measured with a standard hydrogen electrode. Then, **Gibb's Free Energy** ($\Delta G$) is essentially the amount of energy that a reaction yields. The two are related to each other through the Nernst equation:

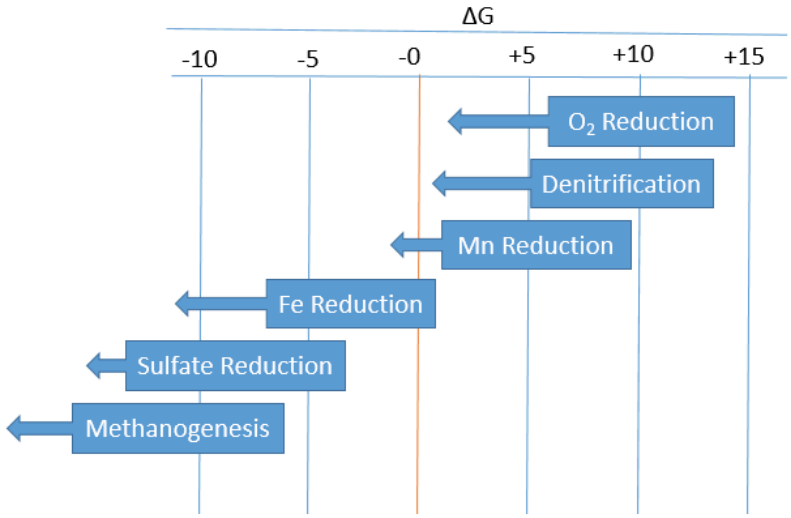
$$\Delta G^0 = -nFEh^0$$

Though the details are beyond the scope of this book, you can see from the equation that Gibb's Free Energy ($\Delta G$) is directly proportional to redox potential ($E_h$). Going down the redox ladder, Eh decreases, and therefore $\Delta G$ also decreases.

This table shows how Eh decreases going down the redox ladder, in volts:

| **Reduction Half-Reaction** | **$Eh^0$ (V)** ***At pH = 0*** | **$Eh_7$ (V)** ***At pH = 7*** |
|---|---|---|
| $O_2 + 4H^+ + 4e^- \leftrightarrow 2H_2O$ | 1.23 | 0.8 |
| $NO_3^- + 6H^+ + 5e^- \leftrightarrow 0.5N_2 + 3H_2O$ | 1.26 | 0.7 |
| $MnO_2 + 2e^- + 4H^+ \leftrightarrow Mn^{2+} + 2H_2O$ | 0.62* | 0.52* |
| $Fe^{3+} + e^- \leftrightarrow Fe^{2+}$ | 0.77* | -0.21 to 0.77* |
| $SO_4^{2-} + 10H^+ + 8e^- \leftrightarrow H_2S + 4H_2O$ | 0.31 | -0.21 |
| $CO_2 + 8H^+ + 8e^- \leftrightarrow CH_4 + 4H_2O$ | 0.17 | -0.24 |
| $2H^+ + 2e^- \leftrightarrow H_2$ | 0 | -0.41 |

This figure shows the corresponding amount of energy the reactions in the redox ladder yield:




Reduction reactions. [Source: Caraccid, CC BY SA 4.0]

Relative favorability of redox reactions in marine sediments based on energy. Start points of arrows indicate energy associated with half-cell reaction. Lengths of arrows indicate an estimate of Gibb's free energy (ΔG) for the reaction where a higher ΔG is more energetically favorable (Adapted from Libes, 2011).[3] Note overlap in ΔG ranges; in soil, this results in cases where multiple types of respiration reactions can occur simultaneously.

## Key Takeaways

- Reduction-oxidation features in soil are important indicators
- Gleyed conditions indicate frequent saturation
- Redox depletions and concentrations indicate a fluctuating water table
- The redox ladder shows the order in which microbes use different oxidizing agents, where oxygen (at the top) yields the most energy, and nitrate (2nd from the top) yields the 2nd most energy, and so forth

CHAPTER 22

# Wetlands and Other Poorly-Aerated Soils

**Rivka Fidel and Amber Anderson**

## Learning Objectives

- Explain how flooding and poor aeration influence soil chemical properties and other functions
- Explain the importance of wetlands for humans and wildlife
- Identify where wetlands are likely to be found
- Describe the key characteristics of hydric soils

**Keywords**: flooding, poorly-aerated soils, wetlands, hydric soils

In previous chapters, we learned that poor drainage and high moisture impede aeration and have a profound impact on soil redox processes. But how does poor aeration affect overall soil functioning? Here we'll examine the effect of poor aeration on wetland soils and soils that have been temporarily flooded.

## General Impacts of Flooding and Poor Aeration

Based on the redox ladder and plants' need for $O_2$, we can see how flooding and other scenarios resulting in poor aeration would affect soil organisms and holistic soil functioning.

## Drowning of typical plant roots

First, as discussed in the soil aeration chapter, typical plants will suffer from insufficient $O_2$ supply to their roots, drowning the roots and eventually causing root rot and plant death. This of course does not apply to plants that naturally grow in poorly aerated soil (see subsection on hydrophytes in the wetlands section below).

## Nutrients and toxins

Next, the redox ladder tells us that once $O_2$ gas is depleted, microbes will begin using other, less efficient electron acceptors (oxidizing agents), starting with $NO_3^-$, then $Mn^{4+}$, then $Fe^{3+}$, and so forth down the ladder. With each step down the ladder, microbes grow more slowly – consequently, they decompose less organic matter, turning less of it into $CO_2$ and allowing more to remain in the soil. For this reason, organic matter tends to accumulate over time in waterlogged, saturated soil. If the flooding is temporary, though, microbes will return to their more rapid aerobic decomposition process and quickly use up the accumulated organic matter.

In the redox ladder, the reduced forms of metals are more soluble. Namely, $Mn^{2+}$ is more soluble than $Mn^{4+}$, and $Fe^{2+}$ is more soluble than $Fe^{3+}$. Consequently, when these metals get reduced (i.e. accept electrons) following flooding, their solubility increases. Over time, if the floodwater does not drain quickly enough, $Mn^{2+}$ and $Fe^{2+}$ may reach toxic concentrations hazardous to typical plants. Beyond metals, certain toxic organic compounds may also accumulate in soil following flooding. Because of the different metabolic pathways involved in anaerobic decomposition ($NO_3^-$and further down on the redox ladder), the anaerobic microbes produce different decomposition byproducts that depend both on the electron acceptor and the organic matter being decomposed (the C in the organic matter becomes the electron donor, i.e. the reducing agent). Some of these C-rich decomposition products are toxic to select plants and animals, and may cause stunting or mortality.

The compounds on the bottom of each redox ladder stair step (the reduced forms) are also frequently more mobile in soil, and some are even gases that quickly exit the soil. Namely, when denitrifying bacteria reduce $NO_3^-$ down to $N_2$ gas, the $N_2$ gas exits the soil. This results in a net loss of soil N, reducing fertility. Similarly, if the soil is flooded for a very long time, $SO_4^{2-}$ can be reduced down to $H_2S$, resulting in a net loss of soil S. The aforementioned reduced metal forms, $Mn^{2+}$ and $Fe^{2+}$, may additionally leach out (albeit slowly) if there is enough drainage following flooding. So some soils may lose cationic metal nutrients following flooding in select circumstances, but the most concerning and impactful nutrient loss in most temporarily flooded agricultural soils is N.

## Air and water quality

Gases lost during flooding can furthermore impact air quality and the climate. Although $N_2$ is inert, the denitrification process actually has several steps, and if the process doesn't proceed all of the way to the end (i.e. if $NO_3^-$ reduction is partial instead of incomplete), it can release various nitrogen oxides. Here are the denitrification reaction steps with notes regarding their impacts (notice how N is reduced in each half reaction):

- Nitrate reduction: $NO_3^- + 2e^- \rightarrow NO_2^- + O^{2-}$
  - Nitrate ($NO_3^-$) is plant-available, but nitrite ($NO_2^-$) is not. So, nitrate reduction lowers plant-available N.
- Nitrite reduction: $NO_2^- + e^- \rightarrow NO + O^{2-}$
  - Nitric oxide (NO) in the products contributes to acid rain
- Nitric oxide reduction: $2NO + 2e^- \rightarrow N_2O + O^{2-}$
  - Nitrous oxide ($N_2O$), found in the products, is a powerful greenhouse gas
- Nitrous oxide reduction: $N_2O + e^- \rightarrow N_2 + O^{2-}$
  - This reaction is beneficial as it uses up the greenhouse gas $N_2O$

Beyond the air pollution, any metals or toxins that become soluble during flooding could potentially leach out into groundwater, but because intense flooding requires slow drainage, this process is expected to be inherently slow.



Poorly drained landscape in Northwest Iowa. See image to the right for a close-up of the soil in this landscape. [Photo Credit: Amber Anderson]



Concentrations near the soil surface in a dark-colored soil in NW IA. This is an indicator of significant wetness. [Photo Credit: Amber Anderson]

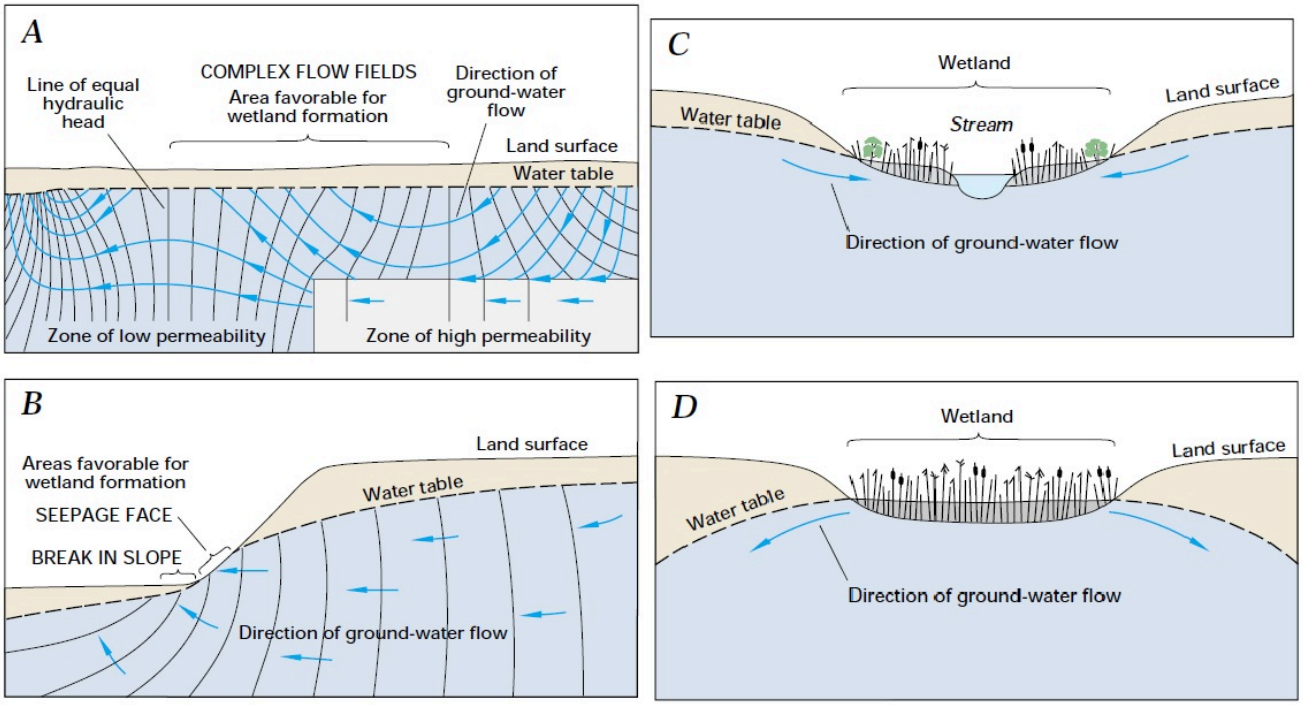
## Wetlands and their Soils

Wetlands are a prime example of areas where reducing conditions dominate, and microorganisms from the lower levels of the redox ladder flourish. Here we define **wetlands** as ecosystems where frequent flooding is both a defining and sustaining feature, such that water has both shaped the ecosystem and become integral to its continued functioning. These ecosystems are home to unique, frequently endangered organisms, and are breeding grounds for many more. Although the means for identifying wetlands vary widely in both science and law, they tend to have 3 key features in common:

- Frequent, regular flooding and saturation ("wetland hydrology")
- Hydric soils
- Hydrophytic vegetation

## Wetland hydrology

Wetlands, as you might expect, feature very poor drainage. They're found at low points of landscapes, in closed basins, and areas adjacent to water bodies such as ponds, streams, estuaries, or lagoons. As mentioned in the soil aeration chapter, areas that are low on the landscape have higher clay content, receive water from uphill, and are closer to the water table – so many such areas become inland wetlands like prairie potholes and swamps. Lakes and streams that frequently flood their banks also help to create wetlands, as do coastal zones subject to rising and falling tides. Layers of frozen water, as in permafrost, do *not* count as wetland hydrology on their own; there must additionally be liquid water present for much of the year.




The source of water to wetlands can be from ground-water discharge where the land surface is underlain by complex ground-water flow fields (A), from ground-water discharge at seepage faces and at breaks in slope of the water table (B), from streams (C), and from precipitation in cases where wetlands have no stream inflow and ground-water gradients slope away from the wetland (D). [USGS Circular 1139]

## Example wetland landscape: Closed depression

In some parts of the upper Midwest, such as Central Iowa, closed depressions as common. These soils can be ponded for significant periods during the year, making annual row crops a poor match for the area. Soil features can include dark soil colors to considerable depth, finer soil textures than the surrounding area due to more recent deposition.

This example (below) was dug in the fall, and had collapsed by the spring due to these soil properties. The water seeping into the pit is additionally a sign of poor drainage and wetland hydrology.



Digging a pit in a poorly drained soil [Photo Credit: Amber Anderson]



The same soil pit had collapsed and filled with water months later [Photo Credit: Amber Anderson]

## Hydric Soils

Over hundreds to thousands of years, soils experiencing wetland hydrology become **hydric soils**. Hydric soils have the following defining characteristics:

- **Gleying** (greying) largely due to the reduction of Fe minerals
- **Red, orange or yellow colors** near plant roots (in contrast with the grey)
- **Mottling** or other **redoximorphic features** where patches of gleyed (grey) soil known as **redox depletions** are interspersed with colored iron concretions (red, orange, yellow, or brown)
- **Dark organic matter accumulations** due to slow organic matter decomposition under low oxygen conditions



Notice how the organic matter in the top half of this profile is so dark that it obscures potential redoximorphic features. This soil cut is from an area drained for peat harvesting in Northeast Minnesota. [Photo Credit: Amber Anderson]

Not all of these soils show all of the properties (at least, not visibly). Many do not show the grey or gleyed colors, as they may have organic matter to significant depth. In those cases, dark colored soils should be examined for red or rusty spots in the dark background to indicate significant wetness. This example (hand pic) is from the landscape above, demonstrates these spots.

Hydric soils fall under multiple soil categories in the USDA soil classification system. Many are Histosols, and others are categorized as having peraquic or aquic moisture regimes. Some include “Aqu” as a suborder root, such as Aquents, Aquepts, and Aqualfs (see the Soil Classification chapter).

The following table shows how much area different types of wetlands take up. Note how wetlands with organic soils (Histosols) compose only 7.3% of all wetlands:

| Wetland type | Global area (1000s $km^2$) | % of ice-free land area | % of all wetland type |
|---|---|---|---|
| Inland (swamps, bogs etc) | 5415 | 3.9 | 28.8 |
| Riparian or ephemeral/ seasonal | 3102 | 2.3 | 16.5 |
| Organic (i.e. Histosols) | 1366 | 1.0 | 7.3 |
| Salt-affected, including coastal | 2230 | 1.6 | 11.9 |
| Permafrost-affected (Histels) | 6697 | 4.9 | 35.6 |

*Data from Eswaren et al (1996), appearing also in* The Nature and Properties of Soils *by Brady and Weil (2017)*

## Hydrophytic Vegetation

If saturated conditions usually drown plant roots, how do wetland plants survive? In short, they all find some way to get oxygen to the roots. Such water-loving plants are called **hydrophytes**, from *hydro–* meaning "water" and *–phyte* meaning "plant," "love" and "grow." Some hydrophytes, like mangroves and cypress trees, keep portions of their roots above the soil; these aboveground root structures, called *pneumatophores,* then carry oxygen gas to the rest of the roots. Others, like cattails and lotuses, use porous, partly hollow stems called *aerenchyma* to carry oxygen down to the roots. In both cases, the zone near the roots becomes a source of oxygen instead of a sink; this allows soil microbes next to hydrophyte plant roots to get oxygen and oxidize $Fe^{2+}$ to $Fe^{3+}$, resulting in the formation $Fe^{3+}$ minerals of various colors from red to orange and yellow.



A bald cypress in the Atchafalaya Basin of Louisiana. Notice the specialized roots called pneumatophores protruding above the water that help get oxygen gas to the remaining roots underwater. [U.S. Army Corps of Engineers | Public Domain]



Mangroves are hardy shrubs and trees that thrive in salt water, such as in intertidal zones along marine coasts. They have *pneumatophores*, snorkel-like roots, to help them survive flooded conditions. [Ariefrahman | CC BY-SA 4.0]



Great bulrush (*Schoenoplectus tabernaemontani*), a sedge that grows in wetlands [Image Credit: Christian Fischer |CC BY-SA 3.0]



Aerenchyma of great bulrush. The porous structures carry oxygen to the plant's roots. [Bb143143 | CC-BY-SA-3.0]

## Importance of Wetlands

Wetlands are uniquely integral to whole-Earth functioning due to the processes and functions that their soils support. First, they host unique, exceptionally diverse flora and fauna. Indeed, although wetlands cover only 6% of land on Earth, 40% of plant and animal species live in wetlands either year-round or during breeding seasons. Wetlands furthermore improve water quality in the region by capturing sediment or phosphorus and denitrifying nitrates in the water. Indeed, wetlands are for this reason frequently called the "kidneys of the Earth." The organic matter accumulations in hydric soils furthermore make them the most carbon-rich soils in the world, and protecting them is therefore integral to fighting climate change.



Wetlands are diverse, and include freshwater habitats such as ponds, wet prairies, and forested wetlands, and saltwater habitats such as salt marshes, mangrove forests and estuaries. [Top to bottom, left to right: Arapaho NWR by Tom Koerner; Sand Lake WRM by Tom Koerner; Delaware Bay by USFWS; Chassahowitzka NWR by USFWS; Aroostook NWR by Keith Ramos; Ding Darling NWR by Liz Barraco; Ash Meadows NWR by Rob Colvin; Francis Biedler NWR by Chris Morris; Forsythe NWR by Becky Longenecker.] More at fws.gov



A small sample showing the diversity of wetland dependent endangered species. [From top to bottom, left to right: Hawaiian moorhen by Gary Kramer/USFWS; mountain sweet pitcher plant by Gary Peeples/USFWS; Hine's emerald dragonfly by Paul Burton; salt marsh harvest mouse by Bjorn Erickson/USFWS; whooping crane by Ryan Hagerty/USFWS; key deer by Kristie Killam/USFWS; swamp pink by Gene Niemien; bog turtle by Gary Peeples/USFWS; California tiger salamander by John Cleckler/USFWS.] More at fws.gov

## Where in the world are wetlands?

We've learned that wetlands are in frequently flooded areas like closed basins and near water bodies. But where are those located exactly? Below are two databases you can use to find wetlands.

- You can view officially recognized wetlands in the US with the **Wetlands Mapper**
    - The wetlands are hard to see at first, but become clearer as you zoom in
- Globally, protected wetlands are inventoried at Ramsar.org. There are 2 ways to navigate:
    - Ramsar Site Map – An interactive map
    - Ramsar Site List – Click on a country, then click "view an annotated summary of the sites" to get a pdf with 1 paragraph description per wetland

## Draining of Wetlands

As beautiful as wetlands are, most crops do not tolerate saturated conditions, and building infrastructure is very difficult in frequently flooded areas. So, historically, farmers and construction companies have resorted to draining wetlands in order to make a living from the land. The most common soil drainage technique is tile drainage, where perforated pipes are installed underground to help move water down and out of the soil faster. In the US hundreds of thousands of hectares of wetlands have been drained or otherwise destroyed in the past few centuries, and less than half of our original wetland area remains.



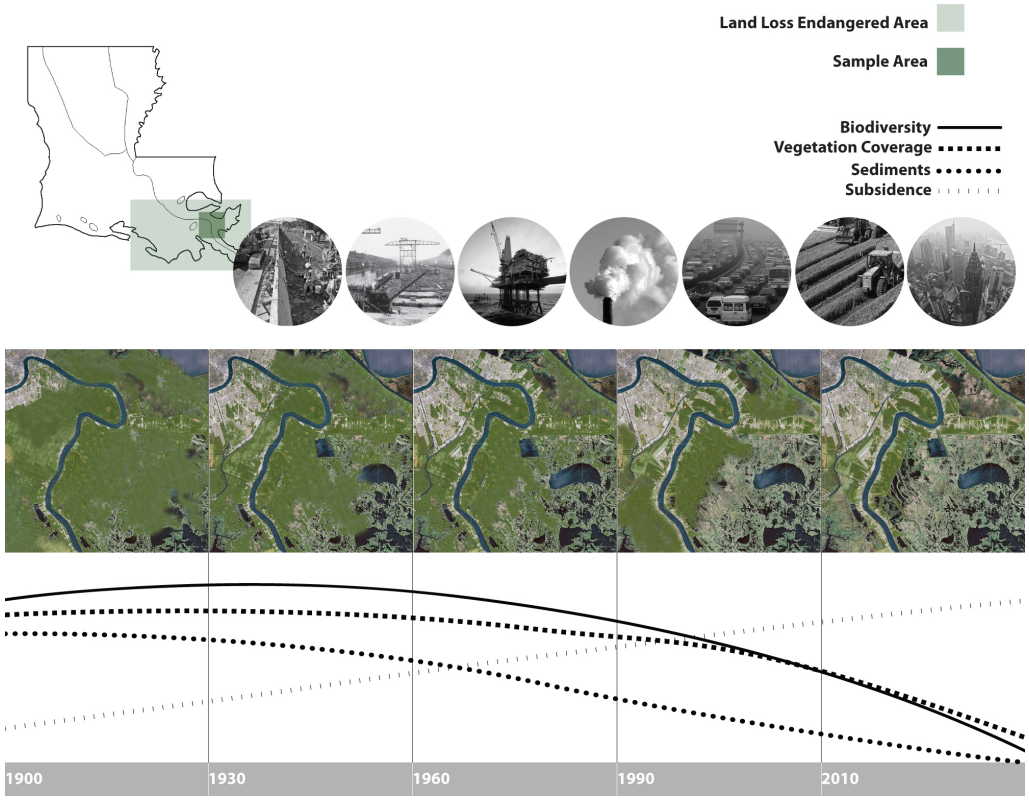
A tile drain being installed at the front lawn of Canterbury Agricultural College. Tile drainage can be used to drain not only wetland soils but also soils that are prone to flooding and/or are too poorly aerated for their intended purpose. [Photo Credit: Ronald Charles Blackmore, 7246 Canterbury Agricultural College tile drain being laid, CC BY 3.0]

## Laws Protecting Wetlands

Thankfully, many governments have in recent decades realized the importance of protecting wetlands. In the US, legal implications can arise from draining these areas for agricultural purposes, as outlined in the Wetland Conservation provision of the 1985 Farm Bill, also known as the Swampbuster Act.[1] These lands could be placed in wetland reserve easements with your local NRCS as part of the Wetlands Reserve Program to preserve the wetland functions while receiving financial incentives.[2]

1. Environmental Protection Agency. (2024). CWA Section 404 and Swampbuster: Wetlands on Agricultural Lands. https://www.epa.gov/cwa-404/cwa-section-404-and-swampbuster-wetlands-agricultural-lands

2. Natural Resources Conservation Service. (n.d.). Wetlands. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/land/wetlands




A section of southern Louisiana that has experienced wetland loss. Black and white circles show human activities contributing to the destruction of wetlands. The graph shows relative (non-quantitative) changes in key parameters: biodiversity, vegetation coverage, sediments, and subsidence. The wetlands in this area depend on sediment inputs from the Mississippi and Atchafalaya rivers, which have declined in recent decades due to dams and other control structures. This decline in sediment input together with wetland drainage have led to sinking of the land, called subsidence. [Image credit Yuting Jiang, The wetland lose of southern louisiana due to human activities | CC BY 3.0]

## Can Wetlands be Restored?

In a sense, yes, but not completely. Once a wetland has been drained or otherwise severely disturbed, it enters a new system state incapable of supporting its former level of biodiversity and ecosystem services. If drained, $O_2$ enters the soil, and aerobic microbes rapidly decompose the soil organic matter, largely turning it into $CO_2$. What took thousands of years of development can be lost in just a handful of years. While you can re-flood the wetland and re-plant any flora that haven't gone extinct, allowing *most* ecosystem services to be largely restored within a few decades, it will take millennia for the soil organic matter to return to what it once was. Furthermore, ecosystem development depends in part on what species were present when at the beginning – and it is impossible to mimic the exact historical conditions with both minimal records and a currently shifting climate. So, while it's possible to restore

most ecosystem services, restored wetlands may never be the same. Similarly, attempts to mimic natural wetlands by constructing man-made ones frequently fall short largely because they haven't had enough time to develop.

## Key Takeaways

- Poorly aerated soils in general are not suitable for growing typical plants, and frequently have:
  - Organic matter accumulations
  - Toxic concentrations of transition metal cations like iron ($Fe^{2+}$) and manganese ($Mn^{2+}$)
  - Toxic organic compounds (usually trace amounts)
  - Gaseous losses of N and S, including greenhouse gases and acid rain precursors
- Wetlands are important because, compared to other ecosystems, they are especially good at:
  - Filtering water
  - Supporting biodiversity
  - Storing organic carbon
- **Wetlands** generally have 3 defining features:
  - **Wetland hydrology:** found in closed basins, depressions, and near water bodies such as lakes, streams, or oceans
  - **Hydric soils:** soils with organic matter accumulations, redoximorphic features (concretions, mottling), and/or gleying
  - **Hydrophytes:** plants that adapted to growing in flooded soil
- The Wetland Conservation provision of the 1985 Farm Bill, also known as the Swampbuster Act, protects wetlands in the US
- After a wetland has been destroyed, it may never be fully restored.
  - Most ecosystem services may be restored in years to decades
  - The exact species distribution and soil properties are extremely difficult to mimic, especially when records are limited
  - Wetlands and other ecosystems take hundreds to thousands of years to fully develop, so we cannot expect them to redevelop fully within our lifetimes, if at all

PART VI

# Soil Chemistry and Mineralogy

CHAPTER 23

# Importance of Soil Chemical Properties

**Rivka Fidel**

## Learning Objectives

- Define: pH, EC, solution
- Explain the importance of soil chemical properties and surfaces
- Sort the solution, surfaces, and solids in order of relative chemical reaction rates

**Keywords**: soil solids, soil solution, redox status, adsorption

## Why are soil chemical properties important?

Soil chemical properties have widespread impacts on countless soil processes, and therefore their importance cannot be overstated. The chemicals in soil, from solid minerals to nutrients and other salts in solution, affect not only plant growth and microbial diversity but also soil greenhouse gas emissions and the transport and breakdown rate of nearly any chemical from nutrients to hazardous substances. Therefore, understanding soil chemistry is vital to understanding and managing soil.

Chemicals are found everywhere in the soil – in fact, soil is *made* of chemicals. As such, soil contains countless chemicals, reacting with each other constantly. The enormous diversity of both chemicals and their reactions in soil can become quite overwhelming but becomes much more understandable when we organize them according to phase: **solids**, **liquids** (here, **aqueous solutions**), and **gases**. Of particular importance in this course are the solids and liquids, and their interactions at the **solid-solution interface**.

## Soil Solids

You may recall that an average soil is about 50% solid particles, where some of these are mineral and some are organic. In soil science, minerals are **inorganic**, meaning they do not contain carbon (with the major exception of carbonates). **Organic** particles on the other hand, do contain carbon – specifically carbon atoms bonded to other carbon atoms, or to hydrogen atoms (thus, carbonates are excluded, as $CO_3^{2-}$ has only C-O bonds).

Minerals are important not only for providing nutrients as they **weather** and dissolve, but also for providing structure to the soil and surfaces for other chemicals to adhere or "adsorb" to (more on this later). Some minerals weather faster, whereas others resist weathering, and as such their chemical properties affect the overall rate of soil formation.

Organic particles release nutrients into the solution as they break down during the **decomposition** process (distinct from weathering, see Soil Life or Soil Organic Matter chapter). Organic matter also has a very high surface area and water holding capacity, helping it to hold onto water and nutrients.

Both mineral and organic particles are found in a wide range of sizes, from >2 mm down to less than 1 micron (that's 0.001 mm). Different size fractions of these particles behave differently in soil, especially in the way they affect the soil solution.

## The Soil Solution

The soil **solution** is all liquid water within the soil and the solutes dissolved within. Solutes include ions, as well as neutrally charged species like sugars and select acids and bases. Gases such as carbon dioxide ($CO_2$) and oxygen ($O_2$) can also dissolve into the solution and react with other solutes, as well as water. During the dissolution process, each molecule of solute is surrounded by water molecules, affecting the behavior of the overall solution.

### Review: *what is a solution?*

A solution is a **homogenous** mixture that is made when a solid or gas has dissolved into a liquid. During **dissolution**, liquid molecules completely surround each molecule of solid (or gas). For example, when table salt (NaCl) dissolves, each $Na^+$ ion is fully surrounded by a sphere of water, and so is each $Cl^-$.

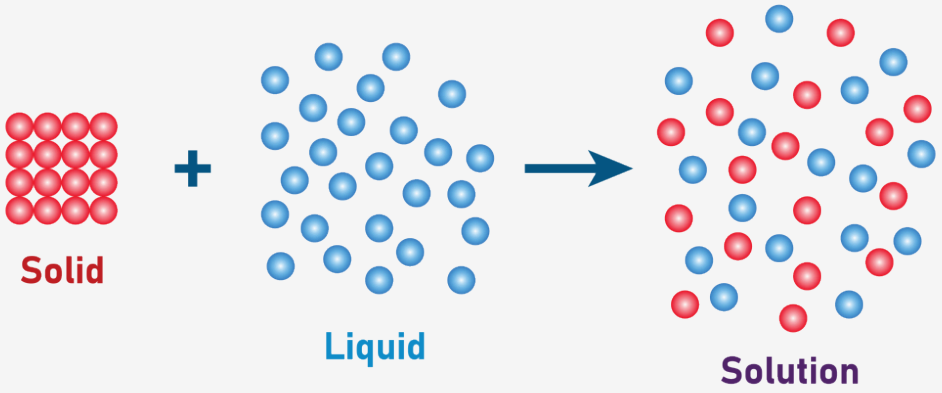



Diagram showing how dissolving a solid in a liquid creates a solution. Notice how each dissolved molecule of the solid (red) becomes fully surrounded by water molecules (blue). [Image Credit: Adobe Stock]

In soil, solid mineral salts like $CaCO_3$, $CaSO_4$ and NaCl are relatively soluble and therefore dissolve readily, becoming part of the soil solution in most soils (albeit at widely varying concentrations depending on the soil's mineral composition and formation factors). Greenhouse gases like carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide ($N_2O$), as products of microbial metabolism, are nearly ubiquitous in soils.

Because solids react very slowly compared to solutes and liquids, and because water is required for most reactions, the solution is where the majority of soil reactions occur. Thus, soil solution properties dramatically affect soil reactions.

Three very important soil solution properties that have cascading effects on soil behavior are pH, redox status, and electrical conductivity. We'll discuss these further in other chapters, but here is a brief overview for now:

- Soil **pH**, an measure of soil acidity and basicity that is calculated as the negative log of the hydrogen ion concentration: $pH = -log[H]$
- **Redox status**, as measured by redox potential (Eh), $[O_2]$, or $[CO_2]$.
  - Redox reactions are greatly influenced by the amount of oxygen and other oxidizing agents in soil such as nitrate.
  - Soil **redox potential (Eh)** is a measure of the electrical potential of soil due to the tendency of the chemicals within it to donate or accept electrons. The more oxygen present, for example, the more important nutrients like nitrogen and iron can become oxidized by donating an electron to oxygen.

- **Electrical conductivity** (EC), a measure of how easily electrons can flow through soil.
  - EC is directly proportional to the total concentration of ions in solution, and thus EC is a good measure of **salinity** or soil "saltiness." Salinity affects numerous soil properties such as aggregation, infiltration, and drainage. It also affects soil osmotic potential and therefore water uptake by plants.
  - The total ion concentration in soil also affects reaction rates, but that is beyond the scope of this class. For more on this advanced concept, see this page on ionic strength or this page on ionic activity.

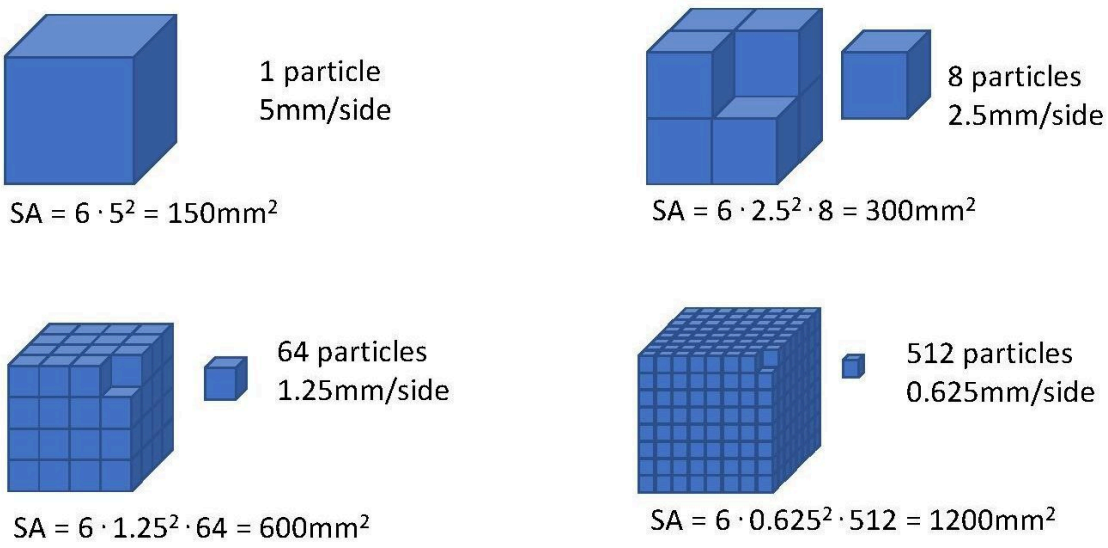
## Soil Surfaces: The Solid-Solution Interface

Due to the very slow reaction rates of solids, the vast majority of reactions with solids occur at the *solid-solution interface*, aka the **surfaces** of soil particles where they meet soil water. These reactions include dissolution of the solids into the solution, precipitation of new solids onto the solution, and adsorption of solutes onto surfaces. (This one of the reasons why particle size and **surface area** are so important in soil science – see below review box for more details).

You can picture **adsorption** as the "sticking" or adherence of solutes to solid particle surfaces. Nutrients and contaminants alike can both adsorb to soil particle surfaces, enabling soil to retain nutrients for plants while keeping contaminants out of the groundwater. Thus, soil surfaces support three important soil ecosystem services: supporting plant growth, providing nutrients, and filtering water. We will learn how this works in upcoming chapters.

### *Review:* Surface Area & Particle Size Relationships

If a large particle is broken down into smaller particles, the total surface area increases. Increasing the surface area can increase the rate of a reaction as more surface area is available for the reaction. Surface Area (SA) of a cube = $6s^2$, where s = the length of one side. When a particle is broken down into smaller pieces, the surface area increases.




[Image Credit: "Surface Area" | Kjh17pchem | CC-BY-SA 4.0 license, cropped.]

## Key Takeaways

- Soil chemical properties affect the soil's ability to provide important ecosystem services such as supporting plant growth and filtering water.
- Important soil chemicals are found in **solids**, the **solution**, and on soil **surfaces** at the *solid-solution interface*.
- Of these, the solution and surfaces are much more reactive than inner portions of solid particles.
- **pH**, **redox status**, and **EC** are all very important soil solution properties that each affect numerous soil behaviors.
- Soil surfaces are unique in enabling **adsorption**, the process by which soil retains nutrients and contaminants. This keeps nutrients in the soil where plants need them while keeping contaminants out of groundwater.

CHAPTER 24

# Mineralogy

**C. Lee Burras**

## Learning Objectives

- Discuss types of minerals present in the soil.
- Understand the importance of mineralogy for soil science.
- Relate mineralogy with Cation Exchange Capacity

**Keywords:** minerals, clays, soil mineralogy.

## Introduction

Soils are minerals. Even the O horizon of a Histosol is more than 70% minerals on a dry mass basis. In any other soil, minerals account for 95 to even 99.99% of the dry mass. The importance of a given mineral in soil is dependent on its prevalence and, especially, its degree of reactivity. It is important to note that soil minerals can be inherited, lost (e.g., dissolved), gained and/or moved in the profile and the landscape depending on natural and human-controlled processes.

## What are Minerals?

Minerals are crystalline solids. Most are naturally occurring and inorganically formed. Individual minerals ("species") are identified and distinguished from one another based on their chemical composition and atomic framework. Restating that, a mineral cannot be uniquely identified from just its chemical composition even though on a day-to-day basis that is often how they are identified. In reality the atomic lattice is a key feature and must be known. For example, "diamond" and "graphite" are independent isomorphic mineral forms of pure "C", yet – as everyone realizes – they have tremendously different physical and chemical properties. Their isomorphic differences are what control their hugely

different value in human societies. Those difference are the function of their bonding strengths across their respective crystalline lattices – aka “atomic frameworks.”

## Types of minerals

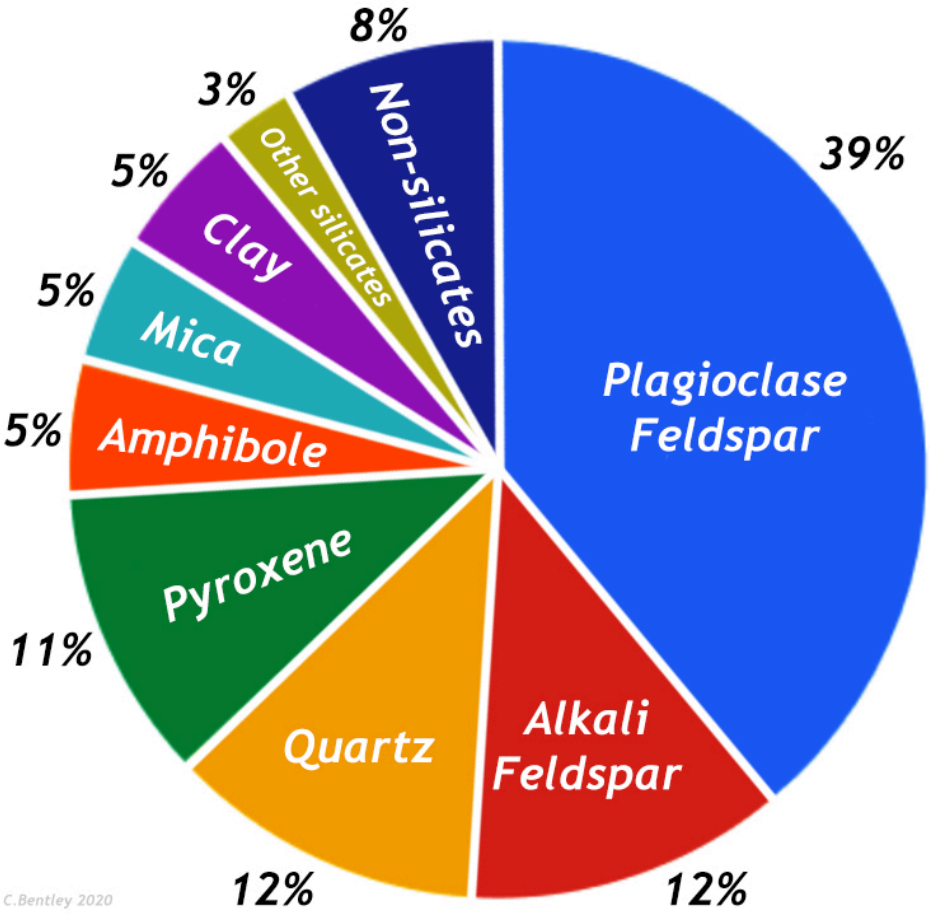
“Calcite” and “aragonite” are more mundane mineral polymorph in soils. Both are composed entirely of “CaCO3” but only calcite is the one commonly found in soil parent materials and calcic horizons. Calcite is also the one mined for ag liming and such. Aragonite is interesting in its own right, though, given it is biologically created mineral. Snails, mollusks, and other gastropods manufacture it into their shells.

Most soils have tens to hundreds of mineral species comprising their solid fabric. Those minerals commonly fall into three common groups: (a) silicates, (b) carbonates and (c) oxides/hydroxides. It is important to note that soil regions in the world also contain significant sulfate, halide and/or phosphate minerals; however, this chapter focuses on the silicates, carbonates and oxides/hydroxides. Two important subgroups within the silicates are the tectosilicates (3D lattice framework of Si-tetrahedrons) and phyllosilicates (2D framework of aluminosilicates comprised of Si-tetrahedral layers bonded to Al- or Mg-octahedral layers).[12]

**Learn more about soil minerals, their composition, and main functional importance:**

- Soil minerals handout [PDF][3]

1. Nelson, S.A. 2015. Phyllosilicates (Micas, Chlorite, Talc, & Serpentine). EENS 2110. Mineralogy. Available at https://www2.tulane.edu/~sanelson/eens211/phyllosilicates.htm , reviewed December 07, 2023.
2. Gaston, L. 2015. Soil Colloids. Agro/EMS 2051. Soil Science. Available at: http://www.agronomy.lsu.edu/courses/agro2051/chap08.htm , reviewed December 07, 2023.
3. Burras, L. (n.d.). *Soil minerals handout*. https://iastate.pressbooks.pub/app/uploads/sites/125/2024/06/Soil-minerals-Burras.pdf




"The most abundant minerals in Earth's crust. The crust is dominantly composed of just a few mineral groups, the vast majority of them silicates." [Image Credit: Callan Bentley 2020, Open Geology | CC BY NC 4.0]

## Importance of Soil Minerals

The importance of a mineral in soil is dependent on its prevalence and/or its degree of reactivity. Prevalence matters because minerals they form the soil's physical framework, accounting for 99.9% of the dry mass in most B and C horizons. In other words, it is the mineral fraction that controls a soil's solid phase characteristics A mineral's reactivity – aka, dynamism – is controlled by its chemical composition, kinetic reactivity, solubility, and/or charge.

There are three pathways whereby a mineral is present in a soil. The most common is inheritance from the parent material. As a result, whatever mechanism that caused the glacial till, loess, volcanic ash, alluvium, colluvium, lava flow – whatever – to be located in a location is what brought or created the original minerals in that soil. The second pathway is some kind of subsequent physical addition. Two common examples of this are aeolian dust and human additions, e.g., ag lime or some fertilizer

including fillers within the fertilizer. The third pathway is pedogenesis during which time an inherited or added mineral dynamically changes form.

The dynamic nature of minerals in soils takes many forms. It can be as simple as hydration – e.g., anhydrite (CaSO4) sorbs (loosely bonds) water molecules onto its surface and creates gypsum (CaSO4*nH20). Hydrolysis is another simple process involving water – e.g., quicklime (CaO) sorbs water molecules, which then split, and the resulting mineral is portlandite (Ca(OH)2). In this process the soil solution gains two H+, which will at least temporarily acidify the soil solution and likely initiate the weathering of another mineral. Hydration and hydrolysis of feldspars are important steps in the conversion of feldspars into phyllosilicates. More broadly, hydration and hydrolysis of rocks and stones coupled with wetting and drying and/or heating and colling results in large soil solids (think boulders, cobbles and gravel) disintegrating into sand or even silt and clay. Oxidation-reduction reactions are likewise simple reactions that routinely dissolve, form or do both with iron- and manganese-bearing minerals. Carbonation drives change in many minerals whenever carbon dioxide (CO2) is introduced in the soil solution. An astute reader will immediately realize that plant and microbial life is constantly added CO2 throughout the root zone with the result always being mineral weathering.

## Mineral Weathering and CEC

A more commonly discussed example of mineral weathering is that of the phyllosilicates, a.k.a., “clay minerals. Soil weathering of illite routinely causes the interlayer potassium (K+) to pop out of its atomic lattice and move into soil solution, where it is routinely uptaken by a plant root. The resulting illite crystal has a slight shift in its tetrahedral basal oxygens and has its layer charge from Al-substitution turn immediately into CEC. Without going into huge detail that simple loss of K+ is the cause of the incredible differences between illite and vermiculite vis-à-vis surface area, CEC and shrink-swell. The vermiculite crystal produced as a result of K+ removal from illite can be highly stable, or, – depending on the distribution of Al-substitution in the Si-tetrahedrons – can rapidly break into smaller pieces where some of the A3+ escapes the atomic lattice. When that happens smectite forms.[4] That smectite has huge physical and chemical differences from its vermiculite parent, just as the vermiculite parent differs from its illite parent. Additionally, the smectite being a very small crystal is able to lessivage deeper into the soil profile; thereby, contributing to the formation of an argillic horizon. Alternatively, if the smectite stays in place it can contribute to vertic horizon characteristics.

Returning to the vermiculite, if its layer charge is remains high (e.g., no escape of Al3+ at its crystal

4. Burras, C.L. 1992. Origin of Smectite in Soils of Western Ohio. PhD Dissertation, 334 p. The Ohio State University Library. Available at: https://etd.ohiolink.edu/acprod/odb_etd/etd/r/1501/10?clear=10&p10_accession_num=osu1487777901658994 , reviewed December 07, 2023.

edges) then the addition of K+ fertilizers can result in “K-fixation” and the recreation of an Illite crystal. Importantly, if ammonium (NH4+) fertilizer is added to that high charge vermiculite then “ammonium fixation” can occur, resulting in a pseudomorph of Illite. Either form of fixation results in less fertilizer nutrient being available than otherwise expected.

To sum the previous paragraphs up, minerals change in soil. They change due to natural processes. They change due to human impacts. Some changes are physical movement. Some changes are chemically driven. Some changes are congruent, which means the complete dissolution of the original mineral. Some changes incongruent, which means the original crystal only partially dissolves, but as a result it turns into a new mineral. In summary, soils are predominately composed of minerals with every one of those minerals prone to change as the soil forms and/or is used by humans. With enough time those changes will drive an incredibly fertile Entisol to become a challenging Ultisol or even an Oxisol.

## Key Takeaways

- Soils are mostly minerals.
- In the A horizon, soil mineralogy influences root growth through nutrient dynamics and available water dynamics.
- In the B and C horizons, soil mineralogy controls soil physical and chemical properties.
- Clay mineralogy is especially reactive although all minerals in soil change at least slowly.

CHAPTER 25

# Introduction to Colloids

**Rivka Fidel**

## Learning Objectives

Upon completing this chapter, you should be able to:

- Define colloid
- Explain the difference between **colloids, clays** and **phyllosilicates**

**Keywords**: crystalline silicates, oxides, hydroxides, colloids

As discussed in the Importance of Soil Chemical Properties chapter, **soil surfaces** serve a very important role as the interface between solid particles and other parts of the soil: water, solutes, and gases. Due to its interactions with water and solutes therein, surfaces are also referred to as the **solid-solution interface**.

Recall that as particle size decreases, **surface area** increases. Therefore, the smallest particles, clay-sized (2 μm) and smaller, have the greatest influence on soil surface area and soil surface properties. Even smaller than clays, at <1 μm, **colloids** have an even greater influence on surface area and therefore soil surface properties. Unlike clays, **colloids** are *any* particle (or liquid droplet) less than 1 μm in diameter. Colloids can be organic or inorganic, and liquid or solid. Even water droplets in clouds and mist are considered colloids! In soil, the **colloidal fraction** refers to all solid particles less than 1 μm in diameter.

## Examples

Below are examples of natural and man-made colloids, according to their phases. For example, smoke has a solid dispersed phase and a gas dispersion medium because smoke is solid particles suspended in air, formed during combustion.

| **Medium** | ***Gas (Dispersed phase)*** | ***Liquid (Dispersed phase)*** | ***Solid (Dispersed phase)*** |
|---|---|---|---|
| **Gas *(Dispersion medium)*** | *No such colloids are known. Helium and xenon are known to be immiscible under certain conditions.* | **Liquid aerosol** Examples: fog, clouds, condensation, mist, steam, hair sprays | **Solid aerosol** Examples: smoke, ice cloud, atmospheric particulate matter |
| **Liquid *(Dispersion medium)*** | **Foam** Example: whipped cream, shaving cream | **Emulsion or Liquid crystal** Examples: milk, mayonnaise, hand cream, latex, biological membranes, liquid biomolecular condensate | **Sol** Examples: pigmented ink, sediment suspended in water, precipitates, solid biomolecular condensate |
| **Solid *(Dispersion medium)*** | **Solid foam** Examples: aerogel, floating soap, styrofoam, pumice | **Gel** Examples: agar, gelatin, jelly, gel-like biomolecular condensate | **Solid sol** Example: cranberry glass |

Below are some examples of colloids:



Aerogels have colloid-sized bubbles dispersed in a solid medium.



Jell-O cubes have colloid-sized water droplets embedded in a solid matrix.



Colloidal silica gel with light opalescence. Silica gels have gas embedded in a solid silica matrix.



Whipped cream has colloid-sized gases in a liquid medium, where liquid is cream.



Milk – emulsion of liquid butterfat globules dispersed in a water matrix.



Hair gel is made of a network of particles in a fluid medium.



Creams are semi-solid emulsions of oil and water.



Opal is a gel in which water is dispersed in silica crystals.



Mist is a colloid-sized water suspended in air (i.e. a liquid colloid in a gas)

[Adapted from "Colloid" on Wikipedia, licensed CC BY-SA 4.0]

Understanding the chemistry of colloids and their surfaces allows us to predict what chemicals –

including nutrients and toxins – the soil can retain. Different types of soil colloids have different surface properties. The two main categories of soil particle types are inorganic and organic. The main categories of clay to colloid-sized inorganic particles, aka minerals, are: crystalline silicate clays (phyllosilicates), quasi-crystalline silicates, and oxides and hydroxides (mainly of iron and aluminum). The organic colloids form their own category. So, all in all there are 4 categories of colloids in soil:

1. **Crystalline silicate clays (phyllosilicates)**: layered minerals containing $SiO_4$
2. **Poorly crystalline silicates**: sphere and tube-shaped minerals containing $SiO_4$
3. **Oxides and hydroxides:** highly weathered minerals containing $O^{2-}$, $OH^{-}$, and $OOH^{3-}$, bonded to transition and post-transition metals (mainly Fe and Al)
4. **Organic colloids:** particles of biological origin <1 μm in size that contain C-H and/or C-C bonds, also called "colloidal humus"

In the upcoming chapters, we'll discuss each colloid type in detail.

## Key Takeaways

- **Colloids** are particles less than 1 micrometer in diameter
- There are 4 types of colloids in soil:
    - Crystalline silicates clays, aka **phyllosilicates** or "layer clays"
    - Poorly crystalline silicate minerals
    - Aluminum and iron oxides and hydroxides
    - Organic colloids, also called colloidal humus

CHAPTER 26

# Phyllosilicate Colloids and their Surface Chemistry

**Rivka Fidel**

## Learning Objectives

Upon completing this chapter, you should be able to:

- Define phyllosilicates
- Explain:
  - the difference between **colloids, clays** and **phyllosilicates**
  - the difference between a **2:1** and **1:1** phyllosilicate
  - what happens when phyllosilicates swell and why **swelling** is important
  - where phyllosilicates get their surface charges from
- Match types of charges (permanent and pH-dependent) with their definitions and where they come from

**Keywords**: colloid types, clay types, phyllosilicates

## Review of Colloid Types

Recall from the previous chapter that colloids are all particles less than 1 micrometer in diameter, and that there are 4 types:

1. **Crystalline silicate clays (phyllosilicates)**: layered minerals containing $SiO_4$
2. **Poorly crystalline silicates**: sphere and tube-shaped minerals containing $SiO_4$

3. **Oxides and hydroxides:** highly weathered minerals containing $O^{2-}$, $OH^{-}$, and $OOH^{3-}$, bonded to transition and post-transition metals (mainly Fe and Al)
4. **Organic colloids:** particles of biological origin <1 μm in size that contain C-H and/or C-C bonds, also called "colloidal humus"

Here we will focus on the first type, **crystalline silicate clays**. The remaining types will be discussed in the next chapter.

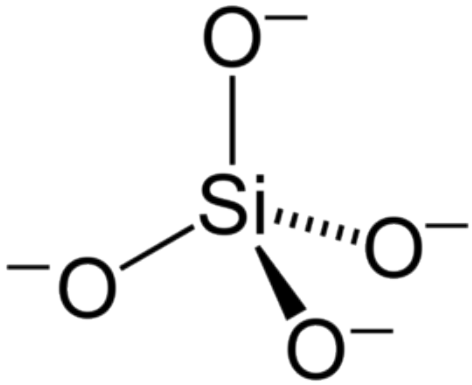
## Crystalline Silicate Clays (Phyllosilicates)

Crystalline silicate clays are the most abundant colloids in most soils, and have a disproportionate effect on soil properties. We've learned that the term "clay" can refer to any mineral particle less than 2 μm in diameter. The majority of these clay particles are **crystalline silicate clays**, also known as **phyllosilicates**. From Greek, "phyllo-" refers to layer, and "silicate" refers to $SiO_4^{2-}$. As reflected in their two names, these important minerals have 3 main properties:

- **Crystalline**: all phyllosilicates have atoms arranged in a regular, near-infinitely repeating structure
- **Layers**: the crystal structure of phyllosilicates is arranged in flat, paper-like layers
- **Silicate**: phyllosilicates all contain **silicate tetrahedra**. Each **tetrahedron** has the formula $SiO_4^{2-}$, but since oxygens are shared, the stoichiometric formula of silicate is frequently written as $SiO_2$ (this is the formula of quartz for example, the dominant mineral in most sand particles).



Baklava is made from phyllo dough, which has layers just like phyllosilicates. The prefix "phyllo-" stands for "layers" in Geology, and is Greek for "leaf" (as in having a thin, leaf-like shape). Geologists adapted the term in modern times, as each layer is thin and broad like an average leaf. [Photo Source: axelslash7 via Pixabay]




A **silicate tetrahedron**. When the oxygens are not bonded to other silicon atoms, it bears a 4- charge. When all oxygens are bonded to other silicon atoms, it becomes neutral.

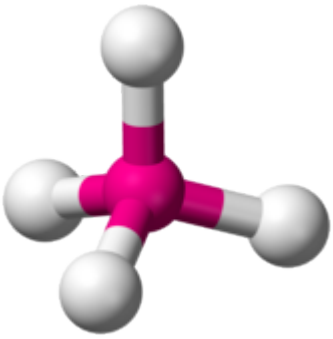
## Check it Out

More on silicate minerals in general can be found in *Physical Geology*, "5.4 Silicate Minerals"[1]

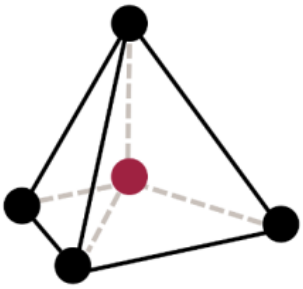
## Phyllosilicate sheets and layering patterns

Phyllosilicates, also known as "layer clays," can be classified according to their layering pattern and chemical composition. Layering patterns are defined by how tetrahedral and octahedral sheets are arranged.

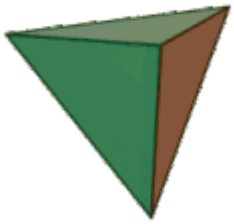
**Tetrahedral sheets** are composed primarily of **silicate tetrahedra**, $SiO_4^{2-}$. In each tetrahedron, the Si is at the center, and is bonded to 4 oxygens arranged in a pyramid-like shape with a triangular base. These can be drawn in various ways.



Ball and stick model of a tetrahedron



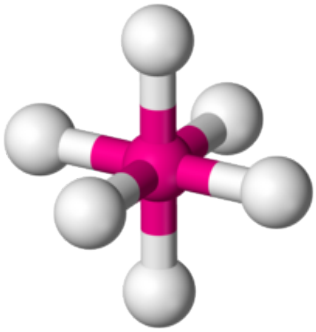
Combination ball & stick and geometric model of a tetrahedron



Animated geometric model of a tetrahedron [Image Credit: Cyp, edited by Peter Steinberg | CC BY-SA 3.0]

**Octahedral sheets** are composed primarily of aluminum and magnesium octahedra. In each **octahedron**, the aluminum or magnesium is located at the center, and is bonded to 8 oxygens. The overall shape resembles two pyramids with square bases, fused at the base.

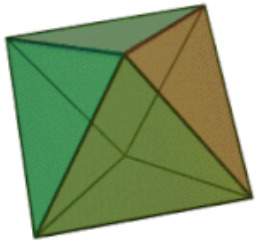
1. Panchuk, Karla. 2019. "5.4 Silicate Minerals." *Physical Geology, First University of Saskatchewan Edition.* http://openpress.usask.ca/physicalgeology/chapter/5-4-silicate-minerals-2.



Ball and stick model of an octahedron

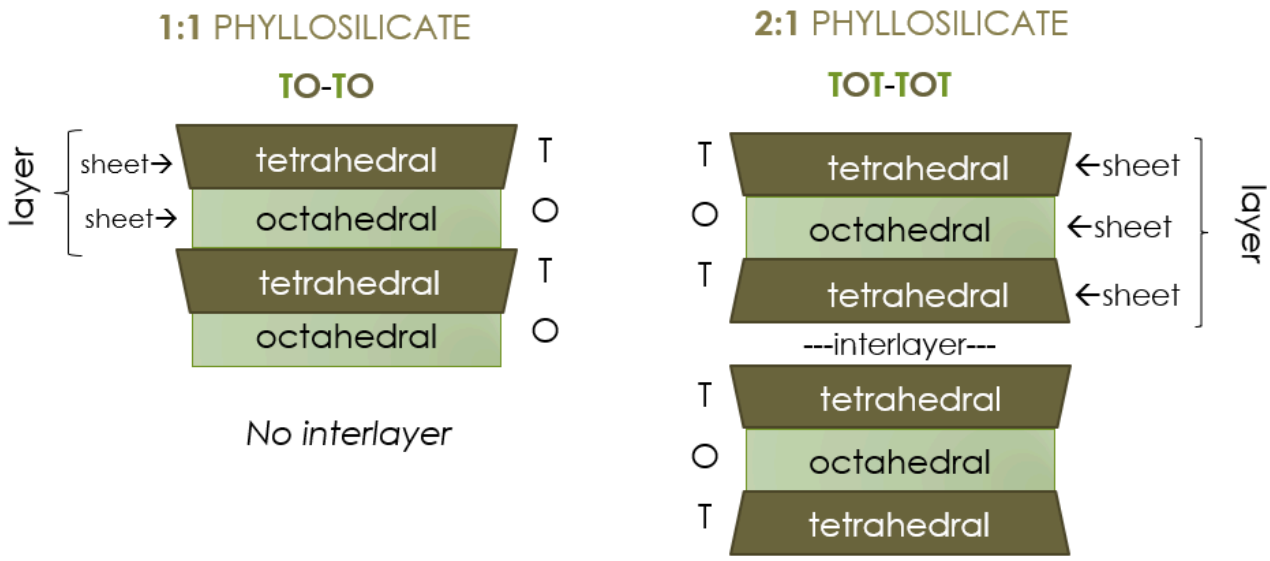


Octahedron drawn using a combination ball and stick model with geometric outline



Animated geometric model of an octahedron [Image Credit: Kjell André, cropped by Stigmatella aurantiaca | CC BY-SA 3.0]

The two main patterns that these sheets arrange into as minerals form are 1:1 and 2:1. In **1:1 phyllosilicates**, there is a one-to-one ratio of tetrahedral sheets to octahedral sheets. These alternate one after the other: tetrahedral, octahedral, tetrahedral, octahedral and so forth (try abbreviating this as TO-TO in your notes). Each layer contains one tetrahedral sheet and one octahedral sheet. In **2:1 phyllosilicates**, there is a two-to-one ratio of tetrahedral sheets to octahedral sheets. These alternate in the order tetrahedral, octahedral, tetrahedral (try abbreviating this as TOT-TOT in your notes). Thus, each layer of a 2:1 phyllosilicate has 3 sheets. In between each 3-sheet layer is an **interlayer**, a space where ions and frequently also water can be found, depending on the mineral in question.




Phyllosilicates (layer clays) structure comparison between 1:1 and 2:1 layer patterns. Notice how trapezoids represent tetrahedral sheets, and rectangles represent octahedral sheets. This is a convention among simplified drawings that don't show atoms or bonds. [Image Credit Rivka Fidel. CC BY-SA 4.0.]

The below figure shows how atoms are arranged in these sheets of two example phyllosilicates.

Notice how the oxygens in each tetrahedral sheet are shared with oxygens in the adjacent octahedral sheet.

Structure of a 1:1 phyllosilicate clay, kaolinite (T-O) and a 2:1 phyllosilicate clay, pyrophyllite (T-O-T). The red arrow represents the Z dimension. T-O-T clays are naturally larger in the Z direction because of the extra layer provided by the additional tetrahedral layer. Each silicon is bonded to 4 oxygens and each magnesium is bonded to 8 oxygens, but the some atoms block each other so not all are visible. Note that kaolinite is common in soil, but pyrophyllite is not.

Structure of a 1:1 phyllosilicate clay, kaolinite (T-O) and a 2:1 phyllosilicate clay, pyrophyllite (T-O-T). The red arrow represents the Z dimension. T-O-T clays are naturally larger in the Z direction because of the extra layer provided by the additional tetrahedral layer. Each silicon is bonded to 4 oxygens and each magnesium is bonded to 8 oxygens, but the some atoms block each other so not all are visible. Note that kaolinite is common in soil, but pyrophyllite is not.

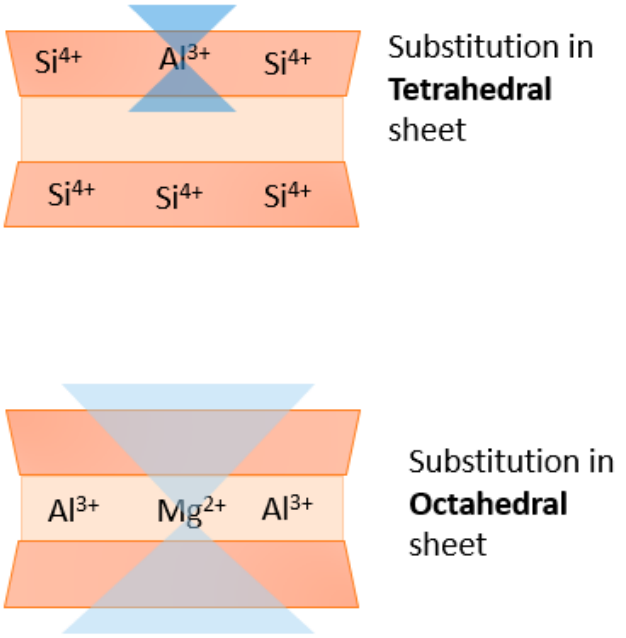
## Sources of charge in phyllosilicates

Charges of phyllosilicates and other colloids are very important because opposite charges attract. A negative surface charge will attract positively charge ions (**cations**), and a positive surface charge will attract negatively charged ions (**anions**). Many important plant nutrients like $NH_4^+$ and $K^+$ are present as cations in soil, whereas others such as $NO_3^-$ and $SO_4^{2-}$ are anions. **Surface charge sites**, places on colloid or clay surfaces where such ion-attracting unbalanced surface charges occur, develop on both inorganic and organic particles. Typically, these charges are only significant among clay and colloid-sized particles, whereas sand and silt contribute negligible charge due to their low surface area and chemical composition (namely their tendency to be enriched in tectosilicates like quartz and feldspar that have fewer unsatisfied charges per unit surface area).

In phyllosilicates, surface charge sites develop inside clay mineral structures during isomorphous substitution, and at crystal edges that form during physical weathering. These processes result in two different types of charge: permanent charge, and pH-dependent charge.

## Permanent charge inside minerals from isomorphous substitution

During the initial formation of phyllosilicates, a process called isomorphous substitution creates what is known as permanent charge inside phyllosilicate crystal structures. In **isomorphous substitution** (or *isomorphic substitution*), a cation of similar size but less positive charge comes in from the solution and replaces the original cation found in the mineral's crystal structure. The name comes from "*iso-*" meaning same, and "*-morph*" meaning shape. Because this substitution occurs when a mineral first forms (*not* during weathering), the degree and location of isomorphous substitution is one of the defining features used to classify phyllosilicates.



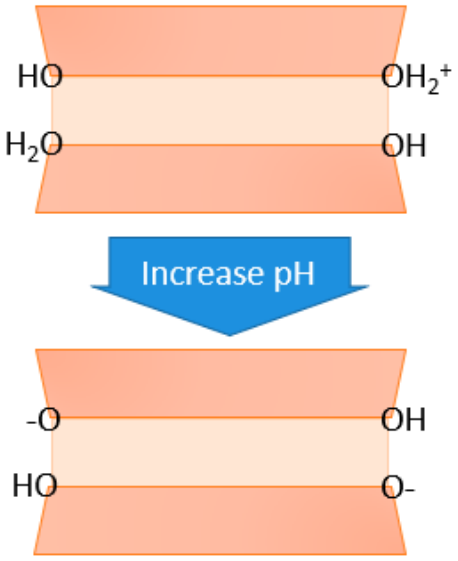

The substitution shown here (+3 instead of +4, or +2 instead of a +3) results in a net negative charge. Since the substituted elements responsible for the charge are not on the surface, they cannot react with H+ in the soil solution.

In **tetrahedral** sheets, $Al^{3+}$ commonly substitutes for $Si^{4+}$. As a result, a Si tetrahedron would become an Al tetrahedron. Because $Al^{3+}$ has a less positive charge than $Si^{4+}$, the overall charge of the tetrahedron becomes more negative by one unit of charge. Thus, the originally neutral tetrahedron will develop an overall -1 charge.

In **octahedral** sheets, $Mg^{2+}$ commonly substitutes for $Al^{3+}$. Consequently, an Al octahedron would become a Mg octahedron. Like in the tetrahedron earlier, the $Mg^{2+}$ has a less positive charge than $Al^{3+}$, so the octahedron's overall charge would decrease by 1, resulting in an overall -1 charge.

In both cases, isomorphous substitution occurs inside a sheet, and so the substituted atoms are *not* in contact with the solution. Thus, the charges that isomorphous substitution creates stay the same despite fluctuations in solution pH and are hence called **permanent charges**.

## pH-dependent charge at crystal edges




On edges, oxygens (O's) are not shared, so without an additional bond to share electrons, charges may develop there. Essentially, cleavage of the phyllosilicate crystals at these edges breaks chemical bonds and leaves oxygens unable to share electrons with adjacent metals or metalloids (Si, Al, Mg, or Fe primarily). This creates an unsatisfied negative charge not being balanced by nearby elements. These edge charges are in contact with the solution, and hence can attract $H^+$ ions when the pH is low. These $H^+$ bind strongly to the surface, becoming part of the surface, and making the overall surface charge more positive (less negative). For this reason, these sites at the broken mineral edges carry what is called **pH-dependent charge** or **variable charge**. This type of charge is found in all minerals, but tends to be greatest in 1:1 phyllosilicates and oxides/hydroxides of iron and aluminum. We'll revisit this in the chapters on cation exchange and anion exchange.

## Key Takeaways

- **Colloids** are particles less than 1 micrometer in diameter, whereas **clays** are particles less than 2 micrometers in diameter
- **Phyllosilicates** are "layer clays", or crystalline silicate clays. These important minerals have 3 key properties:
    - **Crystalline**: all phyllosilicates have atoms arranged in a regular, near-infinitely repeating structure
    - **Layers**: the crystal structure of phyllosilicates is arranged in flat, paper-like layers
    - **Silicate**: phyllosilicates all contain **silicate tetrahedra**. Each **tetrahedron** has the formula $SiO_4^{2-}$, but since oxygens are shared, the stoichiometric formula of silicate is frequently written as $SiO_2$ (this is the formula of quartz for example, the dominant mineral in most sand particles).
- **2:1 phyllosilicates** have (1) a tetrahedral-octahedral-tetrahedral layer pattern, and (2) an

interlayer containing cations, and frequently water

- **1:1 phyllosilicates** have (1) a tetrahedral-octahedral layer pattern, and (2) no interlayer
- When water enters the interlayer of select 2:1 phyllosilicates (vermiculite and smectite), they **swell**
- Phyllosilicates get their charges from **isomorphic substitution:**
    - occurs when similar sized cations of different charges replace cations found in the crystal matrix
    - creates **permanent charge**, which stays constant when pH changes and is always negative in soil
- or **broken edges:**
        - charges are unsatisfied due to broken bonds
        - this creates **pH-dependent charge**

CHAPTER 27

# Common Soil Phyllosilicates

**Rivka Fidel**

## Learning Objectives

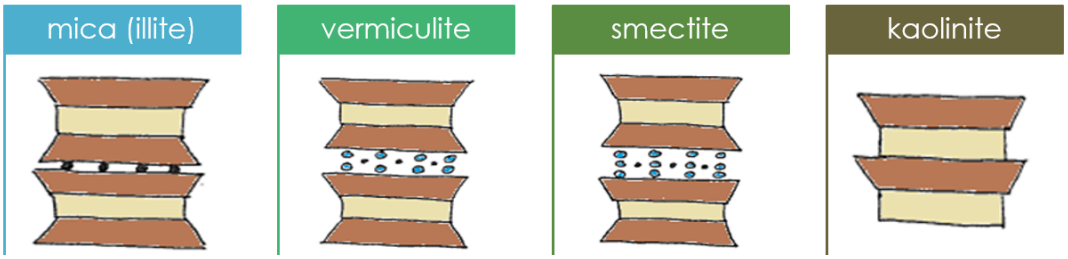
Upon completing this chapter, you should be able to:

- Match phyllosilicate properties with simple diagrams representing each phyllosilicate*
- Explain why and how phyllosilicates in soil vary with respect to degree of soil weathering

**at the University of Arizona and Iowa State University, knowing the details of phyllosilicates is optional for introductory soil science. Elsewhere, please check your course website or ask your instructor.*

**Keywords**: phyllosilicates, types of clay

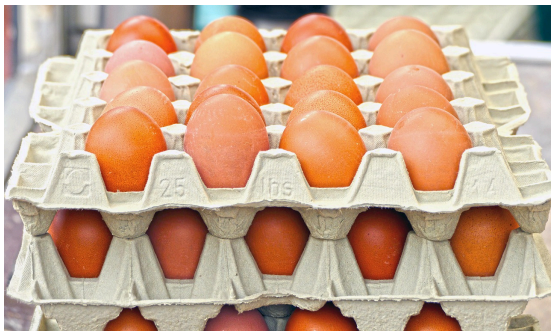
Phyllosilicates are classified based on their layer composition, layering pattern (2:1 vs 1:1), and interlayer composition – which influence their charges and hence ability to hold onto nutrient and/or contaminant ions. Interlayer composition also influences the ability of the mineral to **swell** – a phenomenon where water enters and expands the interlayer. The four most common phyllosilicates in soil, in order of increasing degree of weathering, are mica (frequently as illite), vermiculite, smectite, and kaolinite.




Simplified structural diagrams showing each of the 4 most common soil phyllosilicates. Trapezoids represent tetrahedral sheets, rectangles represent octahedral sheets, blue dots represent water, and black dots represent cations (these vary according to the type of phyllosilicate). [Image Credit: Michael Thompson and Rivka Fidel, CC BY SA 4.0]

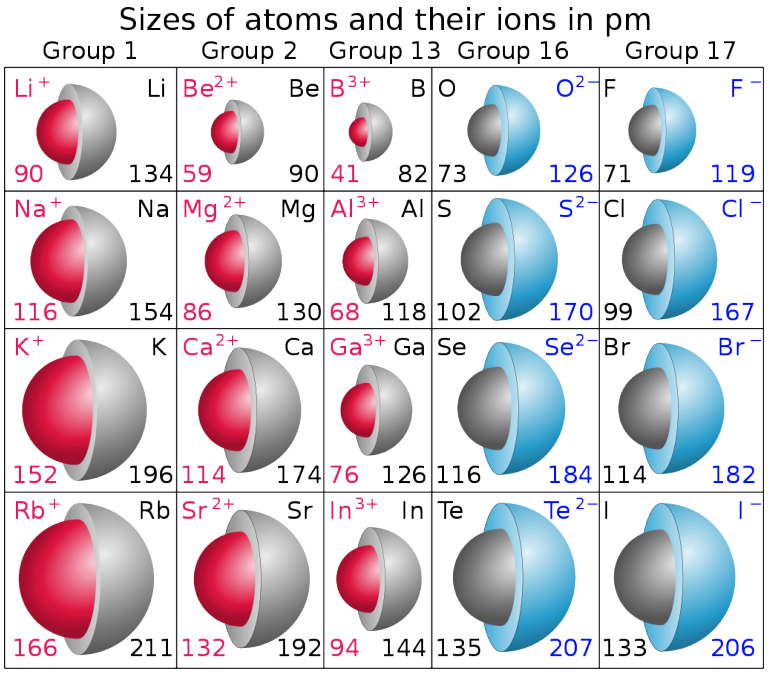
## Mica (Illite)

**Mica** is the least weathered phyllosilicate, a primary mineral (i.e. formed from the cooling of magma), characterized by a 2:1 layering pattern. It undergoes isomorphous substitution in the tetrahedral sheet during formation, leading to copious permanent charges. The interlayer of mica contains $K^+$, but no water. This $K^+$ fits perfectly into little gaps on the interlayer-facing surface of mica, which encourages the interlayer to clamp closed around the $K^+$.



Potassium ions ($K^+$) fit perfectly between mica layers like eggs in stacked egg cartons.

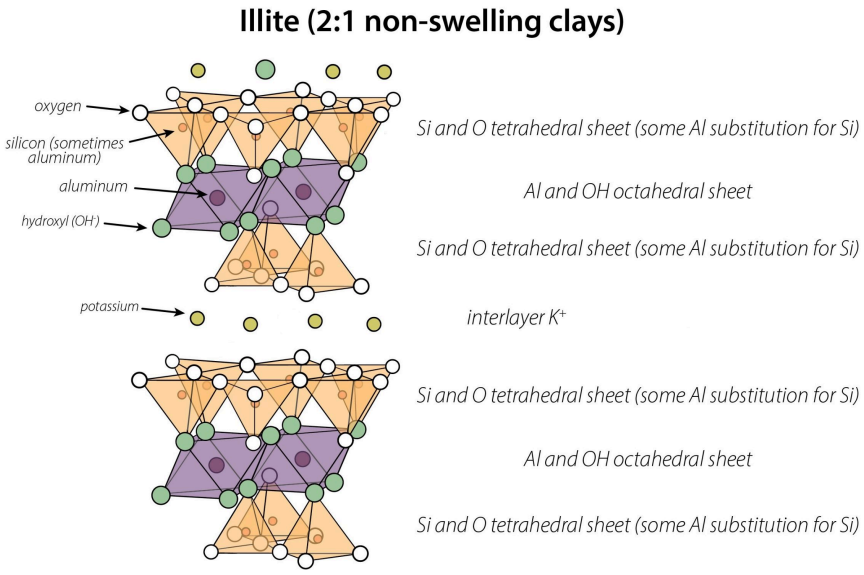
You can think of it like an egg carton – the eggs fit perfectly in egg-shaped divots found in the carton, enabling the carton to close. This tight fit of mica layers around $K^+$ interlayers does *not* allow water to enter, so mica does *not* swell. This limits mica's surface area, limiting its ability to retain ions despite its high permanent charge.




Atomic and ionic radii in picometers (pm) for selected elements. Atomic radii are in grey, and ionic radii are colored. Notice how K+ has a much larger ionic radius than Na+, Ca2+, and Mg2+. Ionic radii of cations increase as you go down the periodic table, and decrease from left to right. [Image Credit: Popnose, CC BY-SA 3.0]

You may have seen microscopic mica particles before, as they frequently lend a slight shimmer to sediments in which they're found. This shimmering property, called luster, makes mica a great mineral glitter used in "natural" makeup and nail polish. It is also used as an additive in other products, for example to improve the properties of drywall, asphalt shingles, and even some electronics.

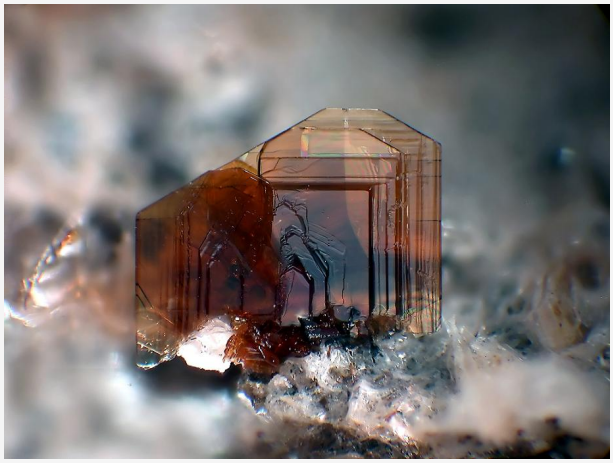
In soil, properties of mica are more variable, and the mica particles are typically smaller due to weathering – so you can't spot them with your naked eye. Such "soil mica" particles typically have fewer layers per particle, and their exact chemical formulas vary from soil to soil. This clay-sized "soil mica" is called **illite**. In this introductory text, we treat mica and illite as synonymous, whereas differences between the two become important in advanced soil science texts.




Crystal structure of an average **illite** mica. [Image Credit: "Clay Mineral Structure" | Paige Quinton, from Komari and Mohan (2021) | CC BY-SA | cropped by Rivka Fidel]



**Muscovite** mica, a felsic mica, does not have much iron and is lighter in color. Notice the flaky layers and high luster (shine) of this sample. [Source: "Muscovite" by Robert M. Lavinsky, CC BY SA 3.0. Cropped.]

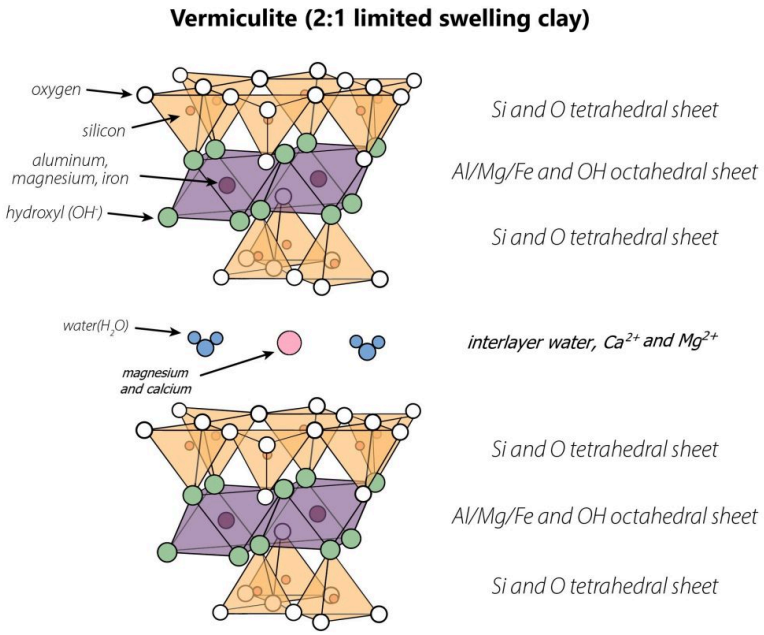


**Biotite** mica, a mafic mica, has more iron and is darker in color. [Source: "Biotite aggregate" by Fred Kruijen, CC BY SA 3.0 Netherlands]

# Vermiculite

**Vermiculite** forms from the weathering of mica (and chlorite, see chlorite box), and is characterized by a 2:1 layering pattern with mostly $Mg^{2+}$ , $Ca^{+2}$, and water in the interlayer. Typically about $1/7^{th}$ – $1/4^{th}$ of tetrahedron in the tetrahedral sheets of vermiculite have experienced isomorphous substation where $Al^{3+}$ has replaced $Si^{4+}$. In soil, $Mg^{2+}$ and even $Mn^{2+}$ may also substitute for a smaller proportion $Al^{3+}$ in the octahedral sheet (perhaps $1/10^{th}$-$1/8^{th}$ of octahedra). This leads to a high permanent charge, but not as much as mica.

Unlike $K^{+}$ in mica, the $Mg^{2+}$ and $Ca^{+2}$ found in vermiculite interlayers do *not* fit into the gaps of the interlayer crystal surface (called "ditrigonal holes"). Instead, $Mg^{2+}$ and $Ca^{+2}$ have smaller ionic radii, and so they "rattle around" in the interlayer. Without a snug fit, they allow water to enter, and the interlayer swells. In sufficiently moist conditions, vermiculite interlayers can have up to two planes of water molecules. This limited expansion leads to a moderate degree of shrink-swell behavior in vermiculites.




Crystal structure of a typical vermiculite. [Image Credit: "Clay Mineral Structure" | Paige Quinton, from Komari and Mohan (2021) | CC BY-SA | cropped by Rivka Fidel]

Vermiculite is used for insulation in homes as well as in potting media. In insulation, the layers are forcibly expanded with air instead of water to create insulating air pockets like in a down jacket. In potting media, vermiculite enhances retention of water and ions.



Expanded vermiculite for use as insulation and in potting mixes. ["Vermiculite" by Jungle Garden is licensed under CC BY 2.0.]

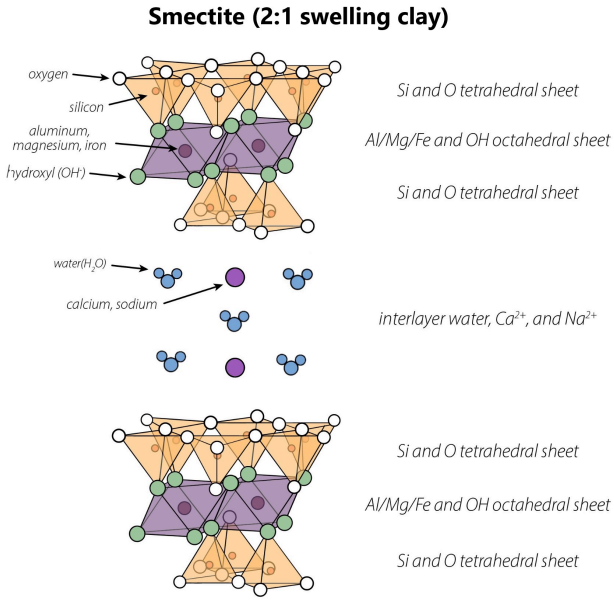


Vermiculite in potting mix. [Source: "Vermiculite" via Wikimedia Commons, public domain]

## Smectite

**Smectite** forms from weathering of mica and vermiculite, and inherits a 2:1 layering pattern from these minerals. Unlike its mineral "parents", smectite exhibits isomorphous substitution primarily in its octahedral sheet, where $Mg^{2+}$ substitutes for $Al^{3+}$. Since octahedral sheets are further from the interlayer, negative charge at the interlayer isn't "felt" as strongly so cations aren't held as strongly in the interlayer. Smectite also has $Ca^{2+}$ in its interlayer, and some smectites in sodium-rich soils and sediments also contain $Na^{+}$ in their interlayers. Together with the more distant and diffuse octahedral charge of smectite, these $Ca^{2+}$ and $Na^{+}$ ions allows for the greatest degree of swelling among the common phyllosilicates: up to 5 layers of water may be present in each interlayer.

Smectites are responsible for the large degree of swelling seen in Vertisols, and other smectite-rich soils likewise exhibit greater shrink-swell behavior than soils lacking in smectites. A common type of soil smectite is called **montmorillonite**. In sediments and sedimentary rocks, montmorillonite is found in bentonite, which is a smectite-rich sediment  primarily composed of montmorillonite (in Geology, bentonite refers to sedimentary rock – a claystone – formed from montmorillonite-rich sediment). **Bentonite** is used to make products like kitty litter because it is water-absorbent and sticky, allowing it to clump together when wet as well. Because smectite particles are very small, they exhibit very slow water permeability, and therefore bentonite is used to line water sampling wells, as well as waste storage lagoons.




Crystal structure of a typical smectite. [Image Credit: "Clay Mineral Structure" | Paige Quinton, from Komari and Mohan (2021) | CC BY-SA | cropped by Rivka Fidel]

## Kaolinite

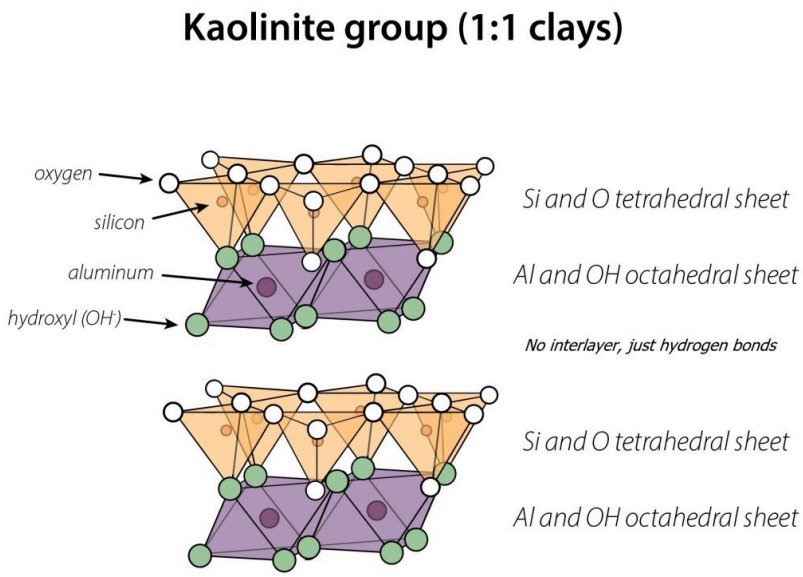
**Kaolinite** has a 1:1 layering pattern, and is the most weathered of the common phyllosilicates. It can form from any other phyllosilicate; for example mica frequently weathers into vermiculite, then smectite, then kaolinite.

Kaolinite's 1:1 layering pattern means there is no interlayer, and hence no opportunity for water to enter or for the clay to swell. Due to its lack of interlayer, kaolinite also

has the lowest surface area of the common phyllosilicates. Additionally, kaolinite has no permanent charge. So, all of its charge originates from broken edges, and is hence pH-dependent.



Hand-made pottery consists of a significant amount of kaolin clays. Glazing pottery (shown here before final firing) uses multiple clay and other minerals, transformed in the heat of the kiln, to create the "stoneware" clay you might purchase from an artisan.



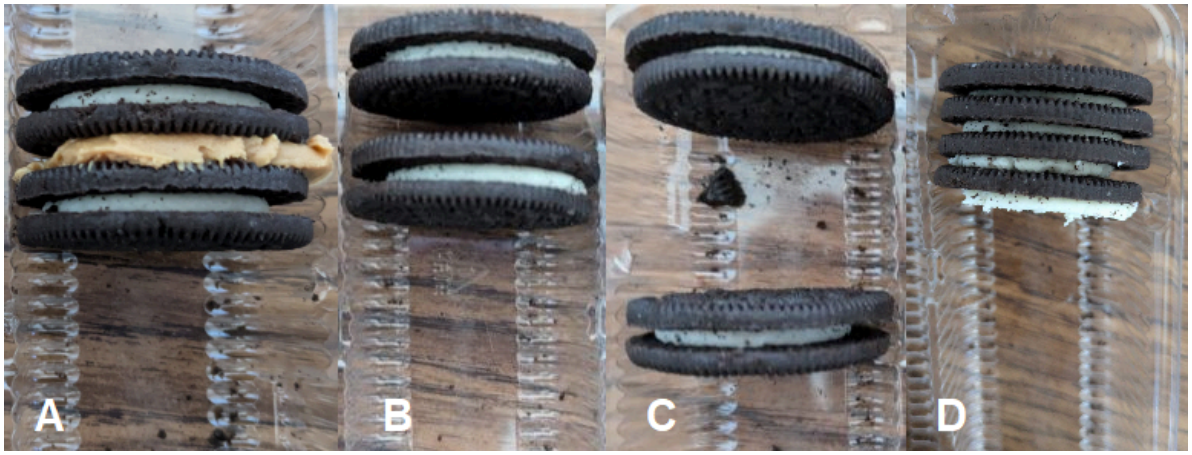

Crystal structure of a typical kaolinite. [Image Credit: "Clay Mineral Structure" | Paige Quinton, from Komari and Mohan (2021) | CC BY-SA | cropped by Rivka Fidel]

The lack of swelling behavior of kaolinite makes it useful for making pottery and infrastructure. Use of kaolinite in pottery and porcelain prevents the cracking and breakage that occurs during drying and/or firing clay when too much swelling clay is included in the potting clay mix. Using kaolinite (typically mixed with sand) underneath roads and buildings also helps avoid the kind of swelling that would cause the ground to rise and fall underneath, resulting in road/building damage.

## Oreo Models of Layer Clays

Did you know you can make models of phyllosilicates with Oreos? Here's what each part of the model represents:

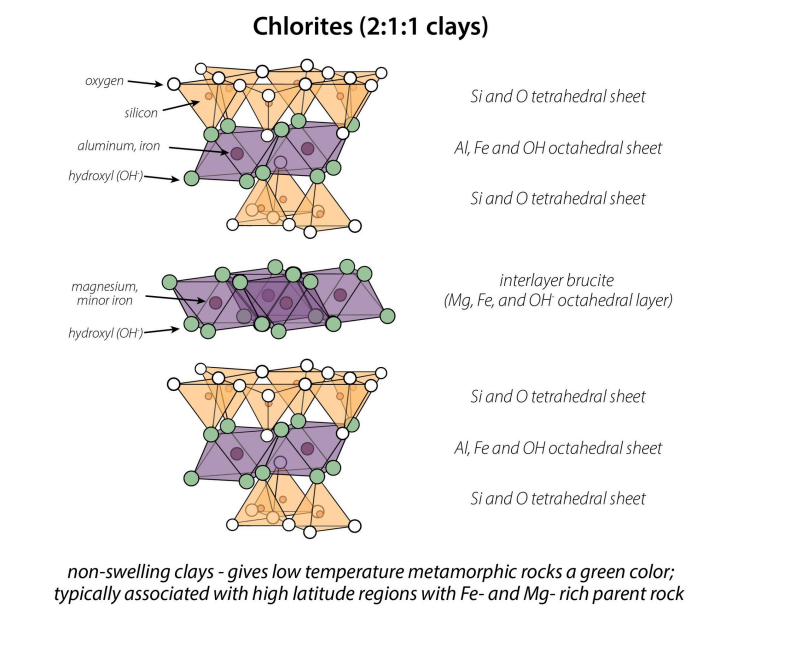
- Cookies = tetrahedral sheets
- Creme = octahedral sheets
- Spaces between cookies = interlayers with water
- Peanut butter = interlayer with potassium ions only




**A. Mica** (Peanut butter represents K+ in the interlayer) **B. Vermiculite** (The limited space between cookies represents limited expansion in the interlayer.) **C. Smectite** (The large space between cookies represents a large degree of expansion in the interlayer.) **D. Kaolinite** (Note how there's cream in between each cookie, representing a TO-TO, or 1:1 pattern. There are no gaps, because kaolinite has no interlayer.)

## Chlorite, a 2:1:1 Phyllosilicate

At the introductory level, we focus on the most common clays in soil, which have 2:1 and 1:1 layering patterns. However, there is a 3rd layering pattern, called 2:1:1. These phyllosilicates, in addition to tetrahedral and octahedral sheets that are bonded to each other, have an octahedral sheet forming in the interlayer. Although at first glance the layers alternate tetrahedral-octahedral, the 2:1:1 layering pattern is unique since the extra interlayer octahedral sheet is distinct in composition from the one found sandwiched between tetrahedral sheets within the layer. This extra interlayer sheet prevents the phyllosilicate from collapsing and expanding, so 2:1:1 clays cannot swell. The most common of these 2:1:1 phyllosilicates is **chlorite**, shown below.




Chlorites. [Image Credit: "Clay Mineral Structure" | Paige Quinton, from Komari and Mohan (2021) | CC BY-SA | cropped by Rivka Fidel]

# Trends among the four main phyllosilicates' properties

You may have noticed some general trends among phyllosilicate properties. With increasing weathering – going in the order mica vermiculite smectite kaolinite – the following trends can be observed:

- Decreasing permanent charge

- Increasing and then decreasing expansion and swelling
- Increasing and then decreasing surface area
- Increasing and then decreasing ion retention

Learn more about ion retention of phyllosilicates and other colloids in upcoming chapters.

## Check it out!

You can examine interactive 3D clay structures online at the Virtual Museum of Minerals and Molecules! Here are direct links to each phyllosilicates from this chapter:

- **mica**: muscovite and biotite
- **vermiculite**
- **smectite,** as found in soil based on research by Dr. David Laird (1991), water omitted
- **kaolinite**

Note that the default view is not the same as what's shown in the figures of this chapter. Use your mouse to rotate the structures until they appear familiar. There are also options to highlight specific elements or parts of each structure.

## Key Takeaways

- Mica is the least weathered phyllosilicate, a primary mineral (i.e. formed from the cooling of magma), characterized by a 2:1 layering pattern.
- Vermiculite forms from the weathering of mica (and chlorite, see chlorite box), and is characterized by a 2:1 layering pattern with mostly $Mg^{2+}$ , $Ca^{+2}$, and water in the interlayer.
- Smectite forms from weathering of mica and vermiculite, and inherits a 2:1 layering pattern from these minerals.
- Kaolinite has a 1:1 layering pattern, and is the most weathered of the common phyllosilicates. It can form from any other phyllosilicate.

CHAPTER 28

# Poorly Crystalline Silicate, Oxide, and Organic Colloids

**Rivka Fidel**

## Learning Objectives

After completing this chapter, you should be able to:

- Compare and contrast types of colloids in terms of:
  - General composition
  - Type or origin of surface charge
  - Where you would expect to find them in abundance

**Keywords**: crystalline silicates, oxides, hydroxides, colloids

## Review of Colloid Types

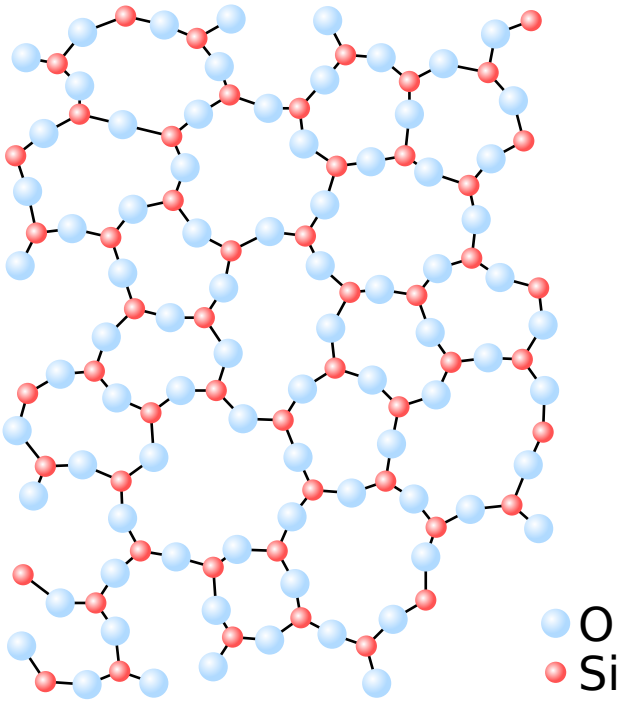
Recall from the previous chapters that there are 4 types of colloids in soil:

1. **Crystalline silicate clays (phyllosilicates)**: layered minerals containing $SiO_4$
2. **Poorly crystalline silicates**: sphere- and tube-shaped minerals containing $SiO_4$
3. **Oxides and hydroxides:** highly weathered minerals containing $O^{2-}$, $OH^{-}$, and $OOH^{3-}$, bonded to transition and post-transition metals (mainly Fe and Al)
4. **Organic colloids:** particles of biological origin <1 μm in size that contain C-H and/or C-C bonds, also called “colloidal humus”

Previously, we discussed the crystalline silicate clays, also known as phyllosilicates or “layer clays”. Here we will discuss the remaining 3 types of colloids.

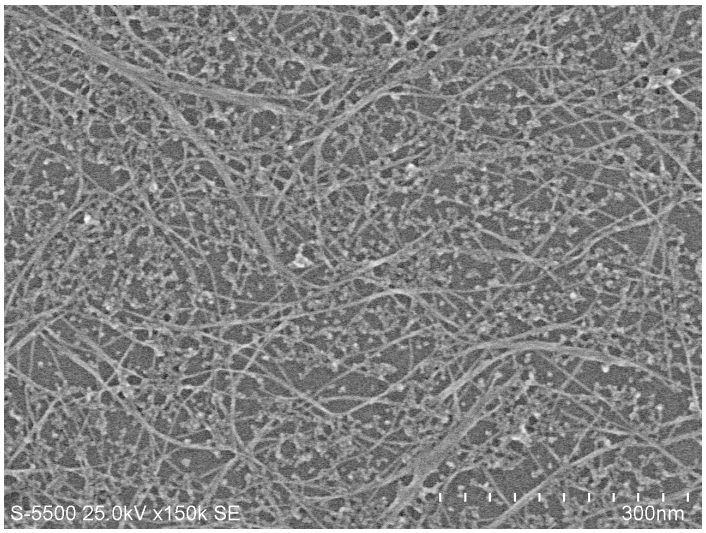
## Poorly crystalline silicates

**Poorly crystalline silicates** are $SiO_4$-based minerals containing what is called “short-range order”, meaning that the patterns in which their elements are arranged only repeat a few times instead of thousands of times or more. They tend to have sphere- or tube-shaped structures, and form during weathering of volcanic ash. Volcanic ash is unique in that it contains very small pieces of **volcanic glass**, so non-crystalline $SiO_4$, instead of more common minerals like quartz, feldspar, and mica. Glass, or “glassy silica” lacks crystallinity because it forms from very rapid to instantaneous cooling of lava. It is from this non-crystalline, glassy precursor that the poorly crystalline silicates get their lack of crystallinity. Indeed, some soil scientists and minerologists consider the crystallinity of these minerals to be so poor that they call them “non-crystalline silicates” instead, grouping them with glass.




Approximate structure of glassy silica, rendered in 2 dimensions instead of 3 (in nature, it is 3-dimensional). Note the lack of regular, repeating patterns. Glassy silica found in volcanic ash frequently becomes poorly crystalline silicates during weathering.

Two of the most common poorly crystalline silicates are **allophane** and **imogolite**. Their sphere and tube shapes help them retain more plant-available water than phyllosilicates and oxides or hydroxides (the latter is discussed later in this chapter). This water retention greatly improves the fertility of **Andosols** (volcanic ash soils). Additionally, allophane and imogolite have substantial pH-dependent charge, helping them hold onto cations and/or anions, depending on the pH.




This Scanning Electron Microscope image shows how synthetic imogolite self-assembles into nanotube structures. These structures are thought to help natural imogolite hold onto water.

## Oxides and Hydroxides

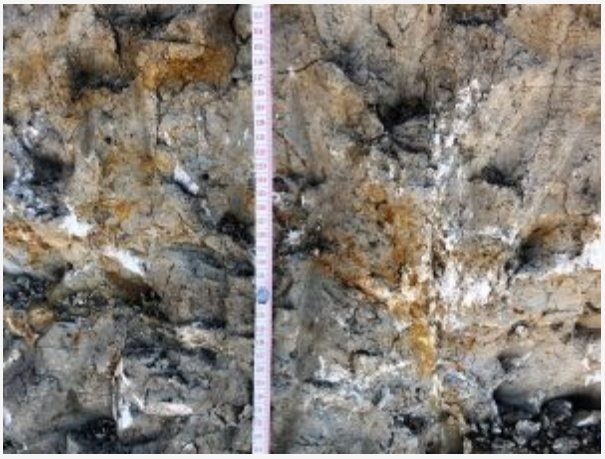
Oxide and hydroxide minerals are the most weathered of the mineral colloids, and are therefore most concentrated in highly weathered soils like Ultisols and Oxisols. They can be crystalline, poorly crystalline, or non-crystalline. Oxide and hydroxide minerals are named after their anions, **oxide**, $O^{2-}$, and **hydroxide**, $OH^{-}$. When oxide and hydroxide are together, they form **oxyhydroxide**, $OOH^{-}$. For simplicity, we refer to oxyhydroxide minerals as a type of oxide mineral, since they contain oxide. In oxide and hydroxide minerals found in soil, the negative charges of these ions are balanced by either $Al^{3+}$, a post-transition metal, or by common transition metal cations like $Fe^{3+}$, $Mn^{4+}$, $Cu^{2+}$, and $Zn^{2+}$. Since Fe and Al are far more abundant in most soils than other transition and post-transition metals, will focus here on Fe and Al oxides and hydroxides.

## Iron oxides and hydroxides

Iron oxide and hydroxide minerals are quite diverse in both structure and color. Iron (III) oxide minerals range from **goethite** (FeOOH), which lends many temperate soils their yellow-to-brown hues, to **hematite** ($Fe_2O_3$), which brings a red color to Ultisols and Oxisols. Iron (II) hydroxides like $Fe(OH)_2$ are found in saturated soils, given that $Fe^{2+}$ normally oxidizes to $Fe^{3+}$ when oxygen is present. These "green rusts" are blue to green in color, and are common in wetland subsoils and clay inclusions in other soils. Iron oxides and hydroxides, like most oxides and hydroxides, exhibit very poor nutrient retention. However, iron specifically can bond strongly with phosphate, keeping this water pollutant and nutrient in the soil.



Gleyed soil conditions



Soil showing redox concentrations (red), depletions (grey), and carbonate accumulations (white)

## Aluminum hydroxides

Unlike iron, aluminum minerals lack color. In soil, aluminum oxides such as corundum ($Al_2O_3$) are rare, because they readily weather into aluminum hydroxides, and therefore aluminum hydroxides dominate. The most common of these is **gibbsite**, $Al(OH)_3$. Gibbsite has stacks of octahedral sheets containing a plane of Al in the center, like in phyllosilicates. Each layer contains about 6 octahedral sheets. However, gibbsite has *only* aluminum, oxygen, and hydrogen – no silicon. So, it is not a silicate. Aluminum in gibbsite does not provide nutrition to plants (it's toxic), but gibbsite can retain a small amount of nutrients – much smaller than other colloids. This is one of the reasons that highly weathered soils, often rich in gibbsite, are not fertile.

This table shows names, formulas, colors and other information about common oxide and hydroxide minerals found in soil.[1]

| Mineral | Formula | Munsell Color Info | Common Color |
|---|---|---|---|
| gibbsite | $Al(OH)_3$ | Any hue, value of 4 to 7 and chroma less than 2 | grey |
| goethite | FeOOH | 10YR 8/6 to 7.5YR 5/6 | Yellow to brown |
| hematite | $Fe_2O_3$ | 5R 3/6 to 10R 4/8 | red |
| lepidocrocite | FeOOH | 5YR 6/8 to 2.5YR 4/6 | reddish-orange |
| ferrihydrite | $Fe\ (OH)_3$ | 2.5YR 3/6 | orange |
| magnetite | $Fe_3O_4$ | Value of 2 or less | black |
| maghemite | – $Fe_2O_3$ | Hue: 2.5YR-5YR | orange-brown |
| todorokite | $MnO_4$ | 10YR 2/1 | black |

## Surface charges of oxides and hydroxides

Oxides and hydroxides generally have small amounts of pH-dependent charge, and little to no permanent charge. This is because their charged functional groups – mainly hydroxyls, aka OH's – are located primarily on the surface, where they can easily accept or donate $H^+$ from the solution.

### Check it out!

You can view interactive 3D structures of various oxide and hydroxide minerals by clicking these links:

- Gibbiste
- Ferrihydrite
- Hematite
- Magnetite

1. This table was adapted from NRCS "The Color of Soil" https://www.nrcs.usda.gov/sites/default/files/2022-11/color-of-soil.pdf with the addition of gibbsite and magnetite.

## Organic Colloids

**Organic colloids** are particles <1 μm in size derived from living organisms that contain primarily C, H, and O. Like all organic matter, these tiny organic matter particles are distinct from carbonate ($CO_3^{2-}$) minerals in that they contain C-C and C-H bonds. Typically, these small particles form during decomposition of larger organic particles such as pieces of leaves, stems, or roots. Some also form from dead microbial cells. Because of relatively large extent of decomposition required to break organic particles down to <1 μm, generally organic colloids are sufficiently decomposed to be considered a part of **humus** (humus can be any particle size, though, since it's defined a highly decomposed, amorphous organic matter).

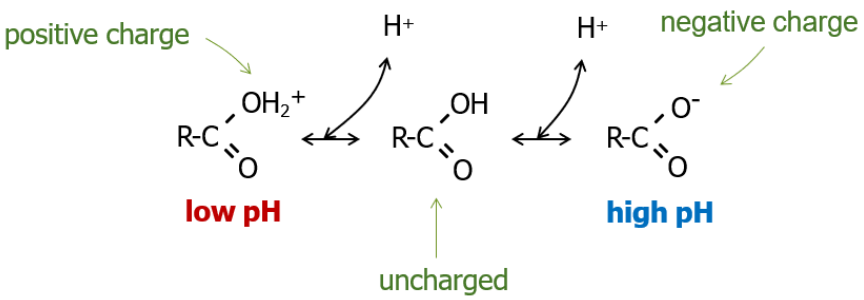
Because organic colloids are a type of organic matter, they are most concentrated in the O and A horizons of many soils. Organic colloids would also be especially abundant in Histosols, given the very large O-horizons found in these wetland soils.

Organic colloids are important for similar reasons that organic matter and colloids in general are important. The area where they really stand out its their ability to hold onto nutrients and filter contaminants. Organic colloids have copious pH-dependent charge sites composed of organic functional groups like carboxylic acids. This lends them a very high cation exchange capacity at neutral to alkaline pH's, which we'll discuss in the next two chapters.

### Example Organic Colloid Surface Charge

One of the most common surface functional groups in organic colloids is carboxylic acid. As pH increases, carboxylic acid donates $H^+$ to the solution, and develops a negative charge.

In the diagram below, "R" is any functional group in an organic matter particle. Carboxylic acid functional groups, as shown in the middle of the figure, have the formula -COOH. Two oxygens are bonded to a central C, and one of the O's is double bonded to the C. The other O is bonded to H. Usually, carboxylic acids only have one H, but in organic matter particles, it's theorized that very large R groups may stabilize the carboxylic acid enough that it could accept another proton.




## Key Takeaways

Here are some important points about the 3 non-phyllosilicate colloids in this chapter:

- **Poorly crystalline silicates**:
  - Sphere- and tube-shaped minerals containing $SiO_4$
  - Form from volcanic ash
  - Abundant in Andosols
  - Very high water retention, moderate nutrient retention
- **Oxides and hydroxides:**
  - Highly weathered minerals containing $O^{2-}$, $OH^-$, and $OOH^{3-}$, bonded to transition and post-transition metals (mainly Fe and Al)
  - Form from very extensive weathering of other minerals
  - Lowest surface charge density of all of the colloids, resulting in the lowest nutrient retention of all of the colloids
  - Abundant in highly weathered soils, found in tropical and subtropical regions
- **Organic colloids:**
  - Particles of biological origin <1 μm in size that contain C-H and/or C-C bonds, also called "colloidal humus"
  - Form from extensive decomposition of dead organisms, primarily plants

    - Highest pH-dependent charge and nutrient retention of all of the colloids
- These 3 colloids all have **pH-dependent charge**, and no permanent charge

CHAPTER 29

# Introduction to Sorption and Ion Exchange

**Rivka Fidel**

## Learning Objectives

When you complete this chapter, you should be able to:

- Define ion exchange and CEC
- Draw a diagram showing how cation exchange works
- Explain the importance of cation exchange capacity (CEC)

**Keywords**: absorption, adsorption, cation exchange capacity (CEC)

## Absorption and Adsorption

Sorption is the process by which soil retains nutrients and filters out contaminants. You can think of it as the soil "holding onto" chemicals. This is important because the more nutrients a soil can sorb, the more it can retain for plant use later, and the less fertilizer is wasted. Sorption also helps the soil retain contaminants, keeping them out of groundwater and nearby streams that are home to wildlife and/or used for drinking water.

As outlined previously, there are two types of sorption:

- **Absorption** = pores sucking up liquid that contains various dissolved compounds (solutes). The solutes then end up *inside* the pore, whether it's between particles or inside a particle.
- **Adsorption** = solutes adhering or "sticking" to the outside of a particle

Because these terms sound similar, it's easy to mix them up. Think of absorption as what a sponge does, absorbing liquids. Whereas, adsorption is more what sticky objects do, like a staticky ballon or microfiber cloth picking up dust.

## Absorption vs Adsorption Analogy: Pie

Another way to think about absorption vs adsorption is to compare eating a pie with a pie to the face. Eating a pie is like absorption because the pie goes inside your mouth. Getting hit with a pie to the face is like adsorption because the pie filling sticks to the outside of your face. Below, Larry from the The Three Stooges demonstrates this analogy:

**Absorption**




Larry eating pie is like absorption because the pie goes inside his mouth.

**Adsorption**




Larry getting hit in the face is like adsorption because the pie is stuck to the outside of his face.

Absorption generally is proportional to water retention, which is discussed in the Soil Water chapter. However, adsorption is related to the surface chemistry of soil particles, especially colloids. Think – why would colloids and/or clay particles have greater effect than silt and sand particles?

### Video Example

Need a clearer picture of sorption? Check out this video: Sorption in Everyday Life

## Factors Affecting Adsorption

Adsorption to soil particles generally follows 2 rules:

- Like polarities attract like, meaning:
  - Polar particles attract polar liquids or solutes
    - Ex: Quartz and glass surfaces are polar, and attract water
    - Ex: Smectite surfaces have polar groups that attract polar pesticides
  - Non-polar solid particles attract non-polar liquids or solutes
    - Ex: the waxy coating on a decomposing leaf is non-polar, and attracts liquid oils from elsewhere in the soil
- Opposite charges attract
  - Negatively charged particle surfaces attract cations (positively charged ions)
  - Positively charged particle surfaces attract anions (negatively charged ions)

This second rule of attracting opposite charges includes both very strong adsorption, such as heavy metals adhering almost irreversibly to colloids, and also weaker adsorption, that is reversible. This reversible adsorption is one of the most important soil processes: **ion exchange**.

## Ion Exchange

**Ion exchange** is the rapid and reversible swapping of ions in the solution with oppositely charged sites on solid soil surfaces. It can happen at any solid-solution interface: where water meets a charged, solid surface. There are two kinds of ion exchange, named after the charge of the adsorbing ion:

- **Cation exchange**: the rapid and reversible swapping of cations in solution with cations on negatively charged surface sites
- **Anion exchange**: the rapid and reversible swapping of anions in solution with anions on positively charged surface sites

Not all ions are created equal. Some are exchangeable, whereas others bind too strongly and do not "unstick" or desorb from surfaces. Here are some of the most common exchangeable ions in soil:

- Exchangeable cations: $H^+$, $Al^{3+}$, $Na^+$, $K^+$, $Ca^{2+}$, $Mg^{2+}$, $NH_4^+$
- Exchangeable anions: $NO_3^-$, $SO_4^{2-}$, $Cl^-$

These ions play very important roles in soil. You may have noticed that most of these ions are plant nutrients: $K^+$, $Ca^{2+}$, $Mg^{2+}$, $NH_4^+$, $NO_3^-$, and $SO_4^{2-}$. Both $Al^{3+}$ and $H^+$ are **acid cations** that lower soil pH (more on pH and acid vs base cations in upcoming chapters). Additionally, $Al^{3+}$ is toxic to plants. $Na^+$ and $Cl^-$, while non-toxic, are still important for affecting overall soil salt levels and the degree of soil clay flocculation and aggregation.

Both types of ion exchange are rapid because the aforementioned exchangeable ions do not bind

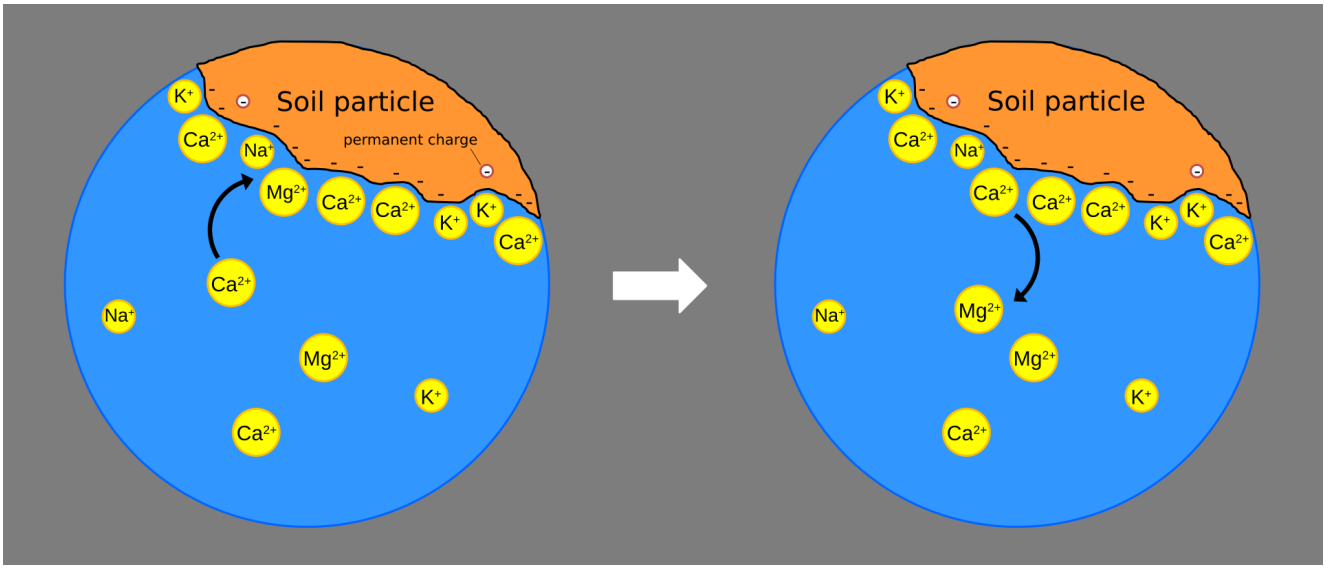
directly to the oppositely charged surfaces, but rather keep a layer of water between them and the surface. You can learn more about this in the Advanced Ion Exchange Concepts chapter.

Note that this process is different from isomorphous substitution. Recall that isomorphous substitution occurs when ions from the solution replace ions *inside* a crystalline mineral like a phyllosilicate. Ion exchange, however, happens on the surface only.

Because 2:1 phyllosilicates are the most common and abundant in most soils, most soils have far more negative charge sites than positive charge sites. Consequently, we will focus on cation exchange in the remainder of this introductory chapter. You can read more on anion exchange in upcoming chapters.

## How Cation Exchange Works

Picture a giant swarm of cations dissolved in water. They flow about with the water, and then suddenly encounter a negatively charged surface. They are attracted to the surface like magnets (although this isn't actually magnetism). When they get closer, they encounter other cations already "stuck" to the surface. But some manage to "bump" some off, and replace them. That is cation exchange.




A calcium ion in solution replaces a magnesium ion on the surface. Note that the charges of the exchanging ions are equal (both are +2).

## Cation Exchange Analogies

You can think of cation exchange as being like a game of musical chairs. Each chair represents a negative charge site, and each person represents a cation. The people walking around the chairs are like cations in solution, and people sitting are like adsorbed cations on the surface. Only one person can fit per chair, so only one cation can fit per site. (Technically, some charge sites can have a -2 charge, and hence either attract one +2 charged cation like Ca2+, or two +1 charged cations like K+. You can think of this as like a double-wide chair.)



Cation exchange is much like musical chairs [Photo Credit: "Musical Chairs" | Mark6Manuo | CC BY 2.0]

Another analogy is cats on laps. Most cats do not like to share a human lap with anyone. So, when a second cat approaches, the first cat leaves, and the cats swap just like cations. Here the lap is a negative charge site, and each cat is a cation.



In the cats-on-laps analogy, each cat is a cation and each lap is a negative surface site with equal charge to each cat. [Image Generated by Rivka Fidel using Adobe Firefly AI]

In the image above, the cat on the floor represents a cation in solution, whereas the cats on laps represent cations adsorbed to negative charge sites. If the cat on the floor hops onto a lap, the cat on the lap will hop off, as shown in the green arrows. This swapping represents cation exchange. Cats

can hop on an off laps, but there can be only one cat per lap, just like there can only be one cation per negative charge site.

Like the other analogy, the cats-on-laps one works best when you consider +1 charge cations and -1 charge sites. But you can picture a +2 cation as a really big cat, and a -2 charge site as a large lap. One big cat, or two small cats, can fit on a large lap – just like one +2 cation or two +1 cations can adsorb to a -2 charge site.

### Video Explaining Cation Exchange Visually

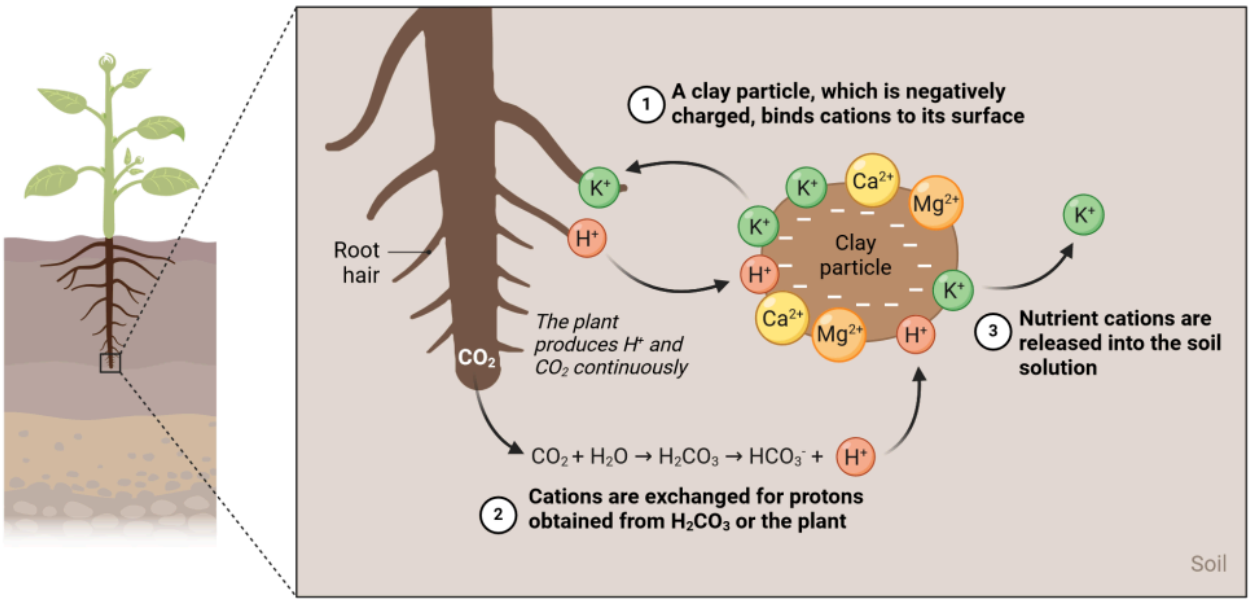
Need a clearer picture of cation exchange? Check out this video: Cation Exchange

## How Plants Use Cation Exchange to Get Nutrients

Adsorption occurring through cation exchange is very important for holding onto plant nutrients, because it keeps the exchangeable nutrient cations from washing away with rainfall. But how do the plants get the adsorbed nutrients back?

Plants are quite ingenious. They release their own cations, mostly $H^+$, to swap with nutrients on soil surfaces (this relies on both pH effects and a phenomenon called "ratio law" discussed in upcoming chapters). Plant roots also produce $CO_2$, which reacts with water to become carbonic acid ($H_2CO_3$), which then supplies even more $H^+$ to exchange with nutrients when it dissociates. In other words, *plants "bump" the nutrients back into solution with acid.* Once in solution, the nutrients can then diffuse or move with the flow of water towards the plant roots.

So, the more cations the soil can "hold on" to via cation exchange, the more ultimately become available to plants, instead of washing away.




How a plant uses cation exchange to get adsorbed nutrients. Note that roots produce both acids and carbon dioxide. The reactions shown in the digram are carbon dioxide ($CO_2$) reacting with water ($H_2O$) to form carbonic acid ($H_2CO_3$) in what's called the **carbonation reaction**, and the carbonic acid dissociating into bicarbonate ($HCO_3^-$) and a hydrogen ion ($H^+$) in what's called an **acid dissociation reaction**. [Created with BioRender.com]

## Cation Exchange Capacity (CEC)

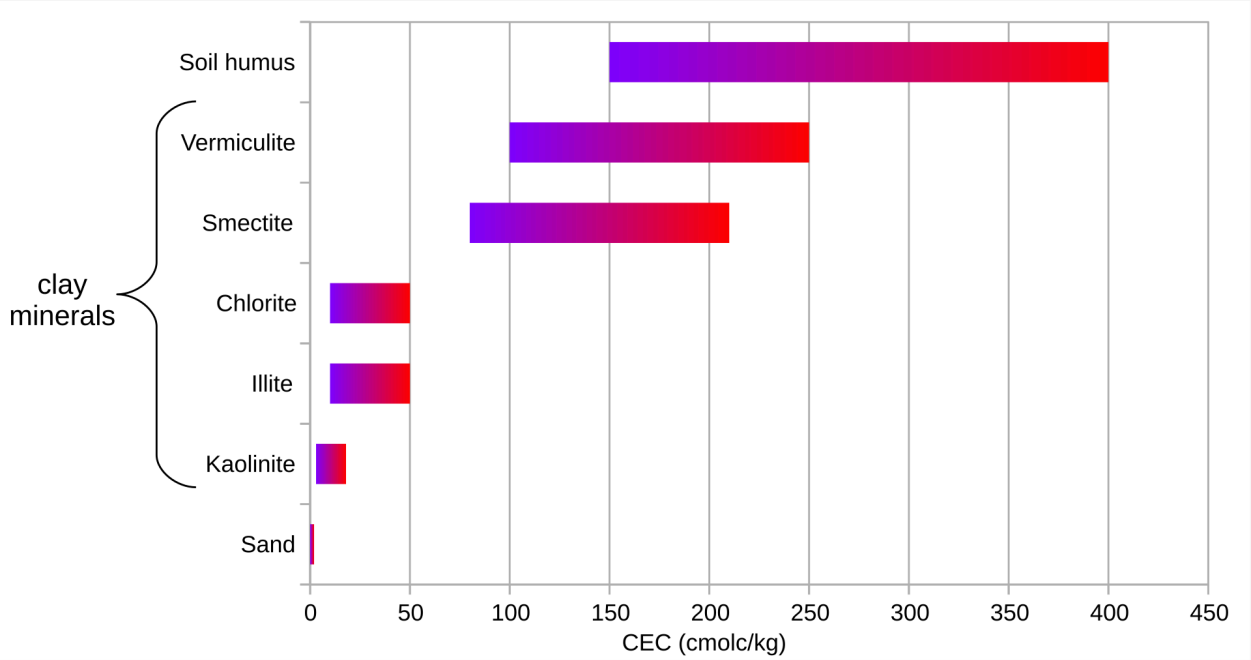
The amount of cations a soil can retain through cation exchange is called **cation exchange capacity (CEC)**. Because the amount of negative charge sites is equal to the amount of cations that can be exchanged, CEC is also equal to the concentration of charge sites per unit mass of soil. CEC is reported in units of centimoles of charge per kg of soil (**$cmol_c/kg$**), which is equal to millimoles of charge (milliequivalents) per 100 g of soil (meq/100g).

Recall that different colloids had different concentrations of negative charge sites. The more concentrated the negative charge sites, the more cations a colloid can hold, the greater its CEC. In most soils, the majority of the negative charges come from phyllosilicates and other clay-sized mineral particles, as well as organic matter. The contributions of sand and silt are negligible. Thus, we can say CEC "comes from" clays and organic matter.

## Diversity of Soil CECs Reflects Soil Diversity

Each soil has a different amount of organic matter, layer clays, and other minerals. The distribution of these important particles is like a “fingerprint” of the soil, in that it is unique – no two soils have the exact same chemical composition. Furthermore, each type of mineral itself can vary in its exact composition from soil to soil, as can the organic matter. For example, smectite in one soil may have undergone more isomorphic substitution than a smectite in another soil. Therefore, the CEC of a smectite in one soil can be different from the CEC of a smectite in another soil.

This is the case for each mineral, and for organic matter. Each one’s CEC can vary from soil to soil, as shown in the figure below.




Plot of typical cation exchange capacities of some common soil materials. Recall that soil humus is decomposed, amorphous organic matter, and that illite is a type of mica common in soil. Notice how 2:1 swelling clays have a higher CEC than other minerals. [Image Source: Kyle MoJo via Wikimedia | CC BY-SA 4.0; Data from: Carroll, D. (1959) Cation exchange in clays and other minerals. Bulletin of the Geological Society of America, 70, 749-780; Brady, N.C., Weil, R.R. (2008) The nature and properties of soil, 14th ed. Pearson, Upper Saddle River, USA. p. 341.; soilquality.org.au Fact Sheet: Cations and Cation Exchange Capacity. Accessed 2017.05.07.]

Some of the minerals are more common in certain soil orders than other, based on degree of weathering and organic matter decomposition. As a result, some soil orders like Histosols have

higher CECs than others. Compare the below table with the above figure, and think about the degree of weathering for each mineral as well as the organic matter in each soil order. Do you notice any patterns?

**Average CEC (pH 7) for some US soils based on USDA Soil Taxonomy[8]**

| Soil Taxonomy order | CEC ($cmol_c/kg$) |
|---|---|
| Ultisols | 3.5 |
| Alfisols | 9 |
| Spodosols | 9.3 |
| Entisols | 11.6 |
| Mollisols | 18.7 |
| Vertisols | 35.6 |
| Histosols | 128 |

## How to determine CEC

There are 3 ways to determine CEC:

1. Sum up the exchangeable cations, in $cmol_c/kg$
2. Take a weighted average of important colloids' known CEC's
3. Cation displacement, where you flood the soil first with one cation, then another cation

See the Cation Exchange Capacity (CEC) Calculations chapter for how to perform the calculations for each method.

## Key Takeaways

- **Ion exchange** = the rapid and reversible swapping of ions in the solution with oppositely charged sites on solid soil surfaces. There are 2 types:
    - **Cation exchange**: the rapid and reversible swapping of cations in solution with cations

adsorbed onto negatively charged surface sites
    - **Anion exchange**: the rapid and reversible swapping of anions in solution with anions adsorbed onto positively charged surface sites
- Exchangeable cations are available to plants because plants can use cation exchange to get nutrients.
    - Plants produce $H^+$ that swap with nutrient cations, forcing them into solution.
    - The plants then take up the cations from the solution.
- **CEC = cation exchange capacity** = the total amount of cations a soil can retain in $cmol_c/kg$

CHAPTER 30

# Cation Exchange Capacity (CEC) Calculations

**Rivka Fidel**

## Learning Objectives

- Identify which CEC formula is appropriate to use with provided data
- Calculate cation exchange capacity using 3 approaches:
    - Sum of exchangeable cations
    - Weighted average of colloid CEC's
    - Quantification of displaced cations

## Ways to Measure CEC

CEC stands for **cation exchange capacity**, the total amount of cations a soil can retain, measured in $cmol_c/kg$ (or meq/100g, but here we'll stick with $cmol_c/kg$).

There are 3 ways to measure and calculate CEC:

1. Quantify and sum up the **exchangeable cations**, in $cmol_c/kg$
2. Take a weighted average of important **colloids**' known CEC's
3. **Cation displacement**:
    1. Replace all of the cations on the surface with $NH_4^+$
    2. displace the $NH_4^+$ with $K^+$
    3. Measure the displaced $NH_4^+$ in solution
    4. Convert units $NH_4^+$ was measured in to $cmol_c/kg$

Some instructors may require you to learn just one of these, whereas others may require all 3. Requirements for a lab course may differ from a lecture course.

# Approach 1: Quantify and Sum Up Exchangeable Cations

## Method

In the first approach, all exchangeable cations are extracted from the soil and then measured. There are various ways to do this, but here's an example:

- Shake up soil with ~1 M $BaCl_2$, $SrCl_2$, or $NH_4Cl$, or $(NH_4)_2SO_4$ solution for 24h
- Allow to settle and filter the supernatant
- Analyze the filtered supernatant for common exchangeable cations in soil, namely: $Al^{3+}$, $Ca^{2+}$, $Mg^{2+}$, $K^+$, $Na^+$ . This is often done with an atomic adsorption analyzer, ion selective electrode, or Inductively Coupled Plasma Mass Spectrometry (ICP-MS).
- $NH_4^+$ can be analyzed only if it is not used in step 1
- $H^+$ can be analyzed by measuring pH, but this "exchangeable" cation isn't *always* exchangeable, and the method isn't always accurate. The issues with the method go beyond the scope of this book, however.

For introductory courses at most institutions, you'll simply be given these data, whereas analysis would wait until an upper-level course. So the important skill for now is learning how to calculate CEC from these data.

## Calculation

When doing this calculation, pay close attention to the units. This will affect whether you need to do a conversion or not.

### Units in Centimoles of Charge per Kilogram (cmolc/kg)

When units are in $cmol_c/kg$, you just need to add up all of the cations. Let's say only 4 cations are measured at the concentrations shown in this table:

| Cation | Concentration ($cmol_c/kg$) |
|---|---|
| $Na^+$ | 2 |

| Cation | Concentration ($cmol_c/kg$) |
|---|---|
| $K^+$ | 3 |
| $Mg^{2+}$ | 5 |
| $Ca^{2+}$ | 15 |

Since the concentrations are already in the desired units, we just have to add them up:

$$CEC = [Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+] + [Al^{3+}] + [H^+]$$

$$= 2\ cmol_c/kg + 3\ cmol_c/kg + 5\ cmol_c/kg + 15\ cmol_c/kg + 0\ cmol_c/kg + 0\ cmol_c/kg$$

$$= 20\ cmol_c/kg$$

Note how we weren't given concentrations of aluminum or hydrogen, so these were assumed to be zero.

### Units in milligrams of cations per kg of soil (mg/kg)

Because different instruments and soil testing services report different units, you frequently will see other units besides $cmol_c/kg$. The most common of these is mg/kg.

To convert from mg/kg to $cmol_c/kg$, we need to use the molar mass from the periodic table, metric orders of magnitude, and the charge of each ion. Here are the steps in words:

- Divide by the molar mass
- Divide by 10 mmol per cmol (because there are 10 millimoles in a centimole)
- Multiply by the charge

## Example Calculation

Soil test results show that a soil contains the following cations in **mg/kg**: $Ca^{2+}$ = 1850, $Mg^{2+}$ = 800, $K^+$ = 530, $Na^+$ = 250, $Al^{3+}$ = 120, and $H^+$ = 20.

From the periodic table we find the following atomic masses in mg/mmol or g/mol (1 g/mol = 1 mg/mmol):

| Element | atomic mass (mg/mmol) |
|---|---|
| Ca | 40 |
| Mg | 24 |
| K | 39 |
| Na | 23 |
| Al | 27 |
| H | 1 |

Now we convert the units for each cation to $cmol_c/kg$ like this:

$$\frac{1850 mg Ca^{2+}}{kg soil} \times \frac{mmol}{40 mg} \times \frac{cmol}{10 mmol} \times \frac{2 cmol_c}{cmol} = 9.25 \frac{cmol_c}{kg}$$

$$\frac{800 mg Mg^{2+}}{kg soil} \times \frac{mmol}{24 mg} \times \frac{cmol}{10 mmol} \times \frac{2 cmol_c}{cmol} = 6.97 \frac{cmol_c}{kg}$$

$$\frac{530 mg K^{+}}{kg soil} \times \frac{mmol}{39 mg} \times \frac{cmol}{10 mmol} \times \frac{1 cmol_c}{cmol} = 1.36 \frac{cmol_c}{kg}$$

$$\frac{250 mg Na^{+}}{kg soil} \times \frac{mmol}{23 mg} \times \frac{cmol}{10 mmol} \times \frac{1 cmol_c}{cmol} = 1.09 \frac{cmol_c}{kg}$$

$$\frac{120 mg Al^{3+}}{kg soil} \times \frac{mmol}{27 mg} \times \frac{cmol}{10 mmol} \times \frac{3 cmol_c}{cmol} = 1.09 \frac{cmol_c}{kg}$$

$$\frac{20 mg H^{+}}{kg soil} \times \frac{mmol}{1 mg} \times \frac{cmol}{10 mmol} \times \frac{1 cmol_c}{cmol} = 2.00 \frac{cmol_c}{kg}$$

Then add up all of the cations' concentrations in $cmol_c/kg$:

CEC = $[Ca^{2+}]$ + $[Mg^{2+}]$ + $[K^{+}]$ + $[Na^{+}]$ + $[Al^{3+}]$ + $[H^{+}]$

= 9.25 $cmol_c/kg$ + 6.67 $cmol_c/kg$ + 1.36 $cmol_c/kg$ + 1.09 $cmol_c/kg$ + 1.33 $cmol_c/kg$ + 2.00 $cmol_c/kg$

= 21.70 cmolc/kg

## Approach 2: Take a Weighted Average of Known Colloids' CECs

Soil particles are not created equal. Some have higher CEC's than others. In particular, the vast majority of surface charge sites, and hence CEC, of most soils comes from clays and organic matter (and mostly from colloid-sized particles thereof). If we know the concentrations of the most common soil

clays, as well as organic matter, we can then use these to estimate the CEC of the soil. To do this, we take a **weighted average** – like you would when calculating your grade.

The general formula is:

$$CEC_{soil} = sum_{i}^{n} F_i CEC_i$$

Where:

- *i* = the individual soil component
- *n* = the number of individual soil components
- $F_i$ = the fraction of the individual soil component
- $CEC_i$ = the cation exchange capacity of the individual soil component

This means that for each soil component (clay or organic matter), you need to multiply the fraction that that component occupies of the whole soil ($F_i$) by that component's CEC ($CEC_i$). Then, add up the products.

Because most of the CEC is coming from soil and clay, we can break this down a bit using another formula derived from the one above:

$$CEC_{soil} = F_{clay} CEC_{clay} + F_{OM} CEC_{OM}$$

Where:

- $CEC_{soil}$ = the cation exchange capacity of the whole soil
- $F_{clay}$ = the clay fraction, from 0 to 1
- $CEC_{clay}$ = the CEC of all clay mineral particles, including multiple clay and colloid-sized minerals like phyllosilicates and oxides/hydroxides
- $F_{OM}$ = the organic matter fraction, from 0 to 1
- $CEC_{OM}$ = the CEC of the organic matter

Each soil has a different suite of clays and/or organic matter contributing to its CEC. In order for this approach to work, the CECs of the clay and organic matter components must be known. Furthermore, since there are multiple clay minerals present in most soils, we must calculate $CEC_{clay}$ before we can plug it into the formula. Assuming that only the 4 most common phyllosilicates are present in the clay fraction, then we can use the formula:

$$CEC_{clay} = F_{mica} CEC_{mica} + F_{smec} CEC_{smec} + F_{ver} CEC_{ver} + F_{kaol} CEC_{kaol}$$

Or more simply:

$$CEC_{clay} = F_m CEC_m + F_s CEC_s + F_v CEC_v + F_k CEC_k$$

Where:

- $F_{mica}$= $F_m$ = the fraction of mica out of total clay
- $CEC_{mica}$ = $CEC_m$ = CEC of mica
- $F_{smec}$ = $F_s$ = the fraction of smectite out of total clay
- $CEC_{smec}$ = $CEC_s$ = CEC of smectite

This is easiest to learn from examples.

## Example Calculations

### Example Calculation with 4 Clays

A clay loam contains 4% soil organic matter, 30% sand, 25% silt, and 38% clay. The clay contains 30% mica, 40% smectite (specifically, montmorillonite), 20% vermiculite, and 10% kaolinite. The CEC's of each colloid component are shown in this table:

| Kind of colloid | CEC ($cmol_c$/kg) |
|---|---|
| Organic | 200 |
| Smectite (ex: Montmorillonite) | 100 |
| Vermiculite | 150 |
| Mica (ex: illite, muscovite, biotite) | 30 |
| Kaolinite | 8 |

First, notice that there is no sand or silt in the formulas, since these have negligible surface charges – so we can ignore the % sand and silt. Now, we have the CEC of the organic matter from the table, but no CEC of clay. So we need to substitute the CEC of clay formula into the general formula. First write the formulas:

$$CEC_{soil} = F_{clay} CEC_{clay} + F_{OM} CEC_{OM}$$
$$CEC_{clay} = F_m CEC_m + F_s CEC_s + F_v CEC_v + F_k CEC_k$$

Next, substitute the second equation into the first:

$$CEC_{soil} = F_{clay}(F_m CEC_m + F_s CEC_s + F_v CEC_v + F_k CEC_k) + F_{OM} CEC_{OM}$$

And then insert the CECs from the table, and the percentages from the prompt *as fractions* (divide by 100 to convert from % to fraction form):

$$CEC_{\text{soil}}$$
$$= 0.38 \left( 0.3 \times 30 \frac{\text{cmol}_c}{\text{kg}} + 0.4 \times 100 \frac{\text{cmol}_c}{\text{kg}} + 0.2 \times 150 \frac{\text{cmol}_c}{\text{kg}} + 0.1 \times 8 \frac{\text{cmol}_c}{\text{kg}} \right) + 0.04 \times 200 \frac{\text{cmol}_c}{\text{kg}}$$
$$= 34.7 \frac{\text{cmol}_c}{\text{kg}}$$

## Example Calculation with 2 Clays

Frequently, the clay component ("clay fraction") is dominated by just 2 common phyllosilicates instead of 4. When a phyllosilicate or other clay-sized mineral isn't mentioned in the prompt, just omit it from your formula or enter it as 0.

A clay loam contains:

- 2% SOM
- 34% sand
- 31% silt
- 33% clay

The clay contains 60% smectite (montmorillonite specifically) and 40% kaolinite.

Assume the CECs of each fraction are the same as in the previous question.

Start with the formula with the $CEC_{clay}$ already substituted in:

$$CEC_{soil} = F_{clay}(F_m CEC_m + F_s CEC_s + F_v CEC_v + F_k CEC_k) + F_{OM} CEC_{OM}$$

Vermiculite and mica aren't present, so we can delete them:

$$CEC_{soil} = F_{clay}(F_s CEC_s + F_k CEC_k) + F_{OM} CEC_{OM}$$

If desired, we can distribute the $F_{clay}$:

$$CEC_{soil} = F_{clay} F_s CEC_s + F_{clay} F_k CEC_k + F_{OM} CEC_{OM}$$

Now we plug in the numbers from the prompt (remember we can ignore sand and silt):

$$CEC_{soil} = 0.33 \times 0.6 \times 100 \frac{\text{cmol}_c}{\text{kg}} + 0.33 \times 0.4 \times 8 \frac{\text{cmol}_c}{\text{kg}} + 0.02 \times 200 \frac{\text{cmol}_c}{\text{kg}}$$
$$= 24.9 \ \text{cmol}_c/\text{kg}$$

## Approach 3: Cation Displacement

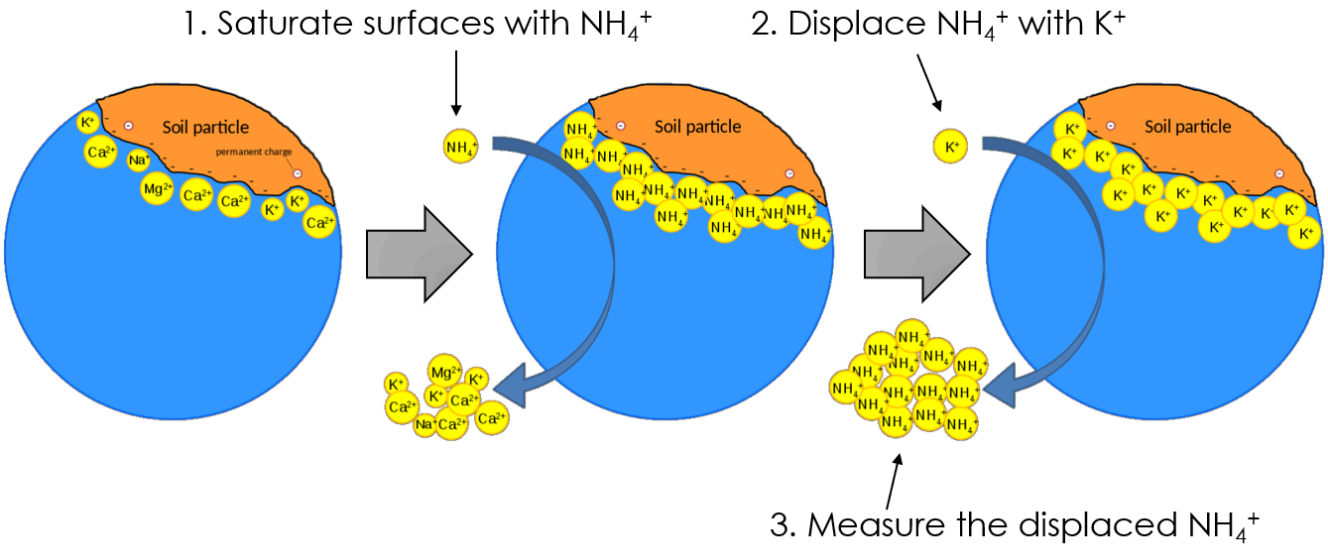
The cation displacement approach is generally regarded as the most robust for determining CEC. This is because it involves an actual exchange reaction, which ensures that you are definitely measuring cations exchanging – not cations that are found in soluble salts like $CaSO_4$, and not cations that are adsorbed too tightly for exchange. This method is commonly used in introductory soil lab courses.

## Method

Recall the steps of a typical cation displacement method:

- Replace all of the cations on the surface with $NH_4^+$
- Displace the $NH_4^+$ with copious $K^+$
- Measure the displaced $NH_4^+$ in solution
- Convert units $NH_4^+$ was measured into $cmol_c/kg$

The idea behind this method is to first flood the surfaces with an easily measurable cation like ammonium ($NH_4^+$), then "bump" that cation off the surface with excess concentrations of a displacing cation like $K^+$, and finally measure the known cation. The approach gets its name from the displacement, the process by which the second cation "bumps" the first off surfaces and into solution. This method relies on a rule of cation exchange called "mass action" or "ratio law" where a very large quantity of a cation in solution will replace virtually all cations on the surface. In the end, the amount of that first cation (ex: $NH_4^+$) in solution is equal to the CEC.




This diagram shows how the ion displacement method works at a molecular scale.

This is typically measured by reacting the $NH_4^+$ with a reagent that changes color based on the concentration of $NH_4^+$. But, the units given aren't normally the desired $cmol_c/kg$, so we have to convert. That is the last step, the calculation. How we do this calculation depends on the units provided. See the example below for how to do the calculation when starting with the most common units, ppm (parts per million, equivalent to mg/L).

## Example Calculation

The final concentration of displaced ammonium ($NH_4^+$) in solution can be easily measured in ppm, which stands for parts per million, and is equal to mg/L. However, we need to convert to $cmol_c/kg$. You might be wondering how we go from having volume (L) in the denominator to mass (kg). This has to do with the solution-to-soil ratio: the volume of solution that is reacted with a given mass of soil.

Let's say that 20 mL of solution are reacted with 5g of soil, and the final concentration of $NH_4^+$ in solution is 60 ppm. Now let's think about what we know, what we don't know, and what we need to cancel out:

- We know that…
  - ppm is the same as mg/L.

- the solution-to-soil ratio is 20 mL:5g soil, or 4 mL/g.
- there's 1000 mL in a L
- there's 1000 g in a kg
- theres 10 mmol in a cmol
- $NH_4^+$ has an absolute charge of 1, so it has 1 $cmol_c$/cmol
- From the periodic table, N has a molar mass of 14 and H has a molar mass of 1. So, $NH_4^+$ has a molar mass of 14+4*1 = 18 g/mol = 18 mg/mmol.

- We want units of $cmol_c$/kg
- We need to cancel out mg and L

Now we can arrange the conversion factors and ratios to convert the units we have (mg/L) to the units we want ($cmol_c$/kg).

$$\frac{60\text{mg}}{\text{L}} \times \frac{1\text{mmol}}{18\text{mg}} \times \frac{20\text{ mL}}{5\text{ g}} \times \frac{1000\text{ g}}{1\text{ kg}} \times \frac{1\text{ L}}{1000\text{ mL}} \times \frac{1\text{cmol}}{10\text{mmol}} \times \frac{1\text{cmol}_c}{\text{cmol}}$$

$$= 1.33\text{cmol}_c/\text{kg}$$

## Key Takeaways

Depending on the data available, CEC can be calculated 3 different ways:

- Sum of exchangeable cations
  - Use when concentrations of exchangeable cations are available
  - CEC = $[Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+] + [Al^{3+}] + [H^+]$
- Weighted average of colloid CEC's
  - Use when percentages or fractions of different colloids such as clays or organic matter are available. Also requires CEC's of each mineral or organic matter fraction, in units of $cmol_c$ per kg of colloid.
  - General formula: $CEC_{soil} = F_{clay}CEC_{clay} + F_{OM}CEC_{OM}$
    - With specific colloids, abbreviated:
      $CEC_{clay} = F_mCEC_m + F_sCEC_s + F_vCEC_v + F_kCEC_k$
- Quantification of displaced cations

- Use when the amount of a cation displaced back into the solution during cation exchange has been provided, such as $NH_4^+$
- This is a unit conversion, so it doesn't have a formula. For example, if 20 mL of solution are reacted with 5g of soil, and the final concentration of $NH_4^+$ in solution is 60 ppm, then we'd calculate:
  - $\frac{60\text{mg}}{\text{L}} \times \frac{1\text{mmol}}{18\text{mg}} \times \frac{20\text{ mL}}{5\text{ g}} \times \frac{1000\text{ g}}{1\text{ kg}} \times \frac{1\text{ L}}{1000\text{ mL}} \times \frac{1\text{cmol}}{10\text{mmol}} \times \frac{1\text{cmol}_c}{\text{cmol}}$

CHAPTER 31

# Soil pH

**Ala Khaleel and Amber Anderson**

## Learning Objectives

- Identify pH values associated with basic or acidic conditions
- Identify basic vs. acid-forming cations
- Discuss the impact of pH on soil and plant growth

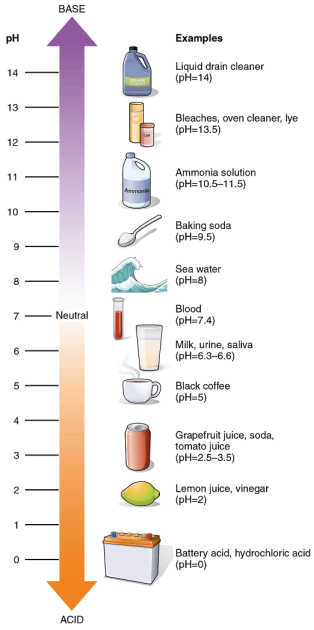
**Keywords:** pH, soil buffering capacity, neutral, alkaline, acidic, ag lime, liming materials

# Soil pH

Soil pH is the measure of soil acidity or alkalinity, specifically the inverse log of the Hydrogen ion concentration on a scale from 0-14. Neutral pH is around 7, with 'acids' being below 7 and 'bases' being from 7 to 14. Therefore, a change from a pH value of 5 to a pH value of 4 indicates a 10x increase in H+.

Most soils have pH values between 4 to 10. Most soils in Iowa have a pH between 5.5 to 7.5. More weathered soils generally have lower pH values, with soils in arid regions having higher pH values due to accumulations of calcium or sodium.

Some soils have higher 'buffering capacity' or ability to resist change. In higher organic matter or those high in particular types of clays, those with higher CEC values, the same management will have a lesser impact on the pH. Therefore, when trying to raise the pH, additional lime or input will be required.




[Image Source: USGS]
Click to enlarge

## Example-buffering capacity

Consider a perfectly hot large coffee pot vs. a cup freshly poured in your hand. Predict which would change temperature most quickly if an ice cube were added.

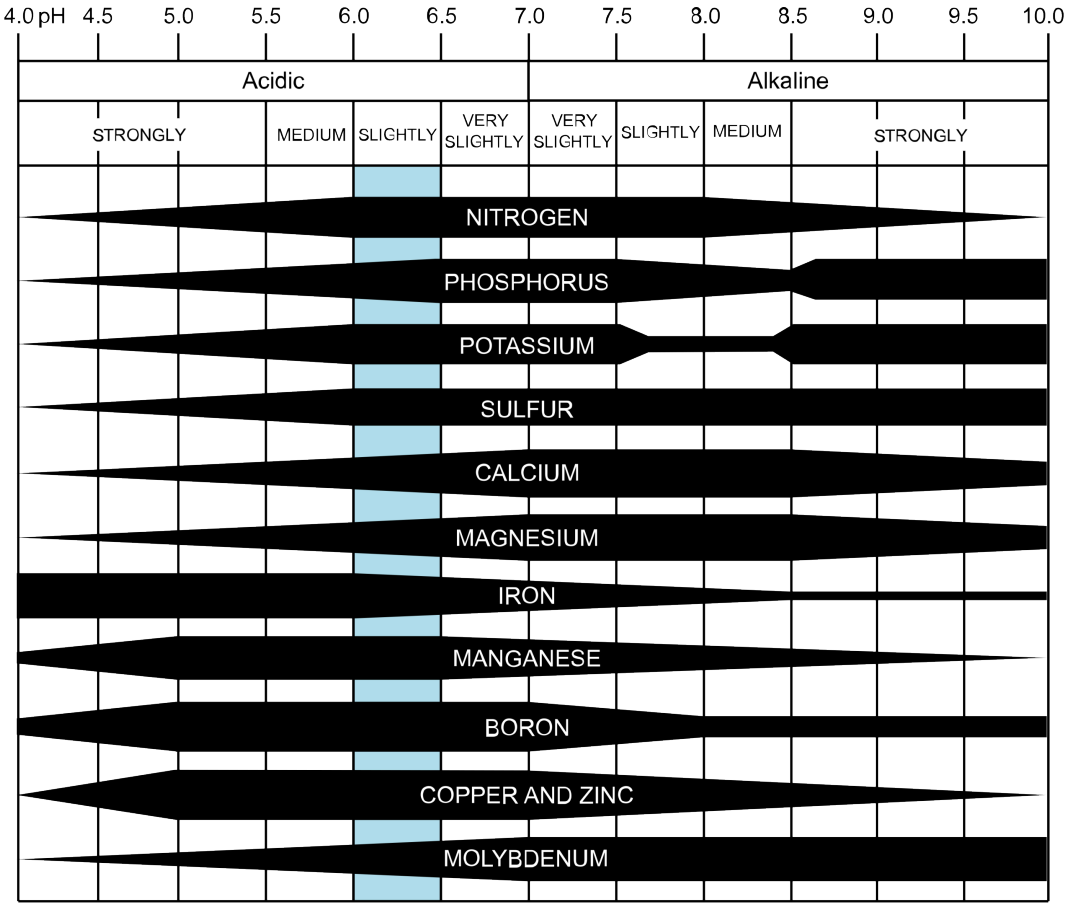
The larger volume of the coffee pot makes the temperature change more slowly than your cup and has a higher ability to resist that temperature change. This would be the higher buffering capacity in the soils example. Small changes in either direction-either an ice cube added or perhaps 30 seconds in the microwave would be expected to have a bigger change on the temperature of your cup than of the large coffee pot.

## Importance

Soil pH is sometimes considered the "master variable" that has several impacts on plant nutrients and plant growth. Soil pH also impacts or interacts with other properties in the soil.

## Soil pH influences

- Amount and availability of plant nutrients; some plant nutrients are more available under acidic conditions, while others are more available under basic or alkaline conditions.
- The activity of soil microorganisms responsible for residue decomposition.
- Charges on soil organic matter and on some mineral surfaces, influencing the soil's cation exchange capacity.




Soil pH effect on nutrient availability. [Image Source: CoolKoon on Wikimedia Commons, available CC BY 4.0]

## Factors influencing pH values in soil

- **Parent material:** original pH of the material.
- **Nitrogen fertilization:** over time, can lower pH values.
- **Management for particular crop:** agricultural lime or 'liming materials' may be added to raise pH,

or elemental sulfur or acidifying materials may be added to lower the pH for a particular target crop.

- **Time:** over time, removal of base-forming cations with weathering or cultivation will decrease the soil pH
- **Buffering capacity:** the soil's ability to resist change or a higher buffering capacity, means that a soil pH will be slower to change with the same action that may more significantly lower the value elsewhere.

### Did you know?

The color of old-fashioned hydrangeas are an indicator of pH, displaying blue flowers in acidic conditions and pink in higher pH-alkaline soils.This hydrangea was photographed in the highland regions in Costa Rica:



[Photo Credit: Amber Anderson]

## Raising the pH

Low pH values in soil may lead to decreased availability of some nutrients-like phosphorus, decreased activity of some organisms-like bacteria, or cause aluminum toxicity in highly weathered soils. Liming materials, such as 'ag lime', generally ground calcium carbonate from limestone, are used to raise pH across the Midwest due to regional mining and presence of limestone bedrock. Dolomitic limestone, or rock containing a higher amount of magnesium carbonate, may be used if magnesium is also needed. Other materials are used if regionally available.

For the lime requirement guidelines, especially for Iowa or the Midwest US, you can consult the Iowa State University soil pH and lime application guidelines (extension publication PM 1688).

### How do we measure pH?

- In the lab, the pH of a soil solution is usually measured with a glass electrode. The soil sample is prepared with either water or dilute salt solution, as the electrode only measures acidity in solution rather than H+ ions held on the soil surface.
- In the field, pH paper strips can be used to get an approximate value to determine the need for further testing or management.

## Key Takeaways

- Soil pH is an important factor in the soil, influencing nutrient availability and organism activity
- pH value of soil is impacted by management, such as crop removal or limining
- pH value can be increased by application of liming materials, or decreased by sulfur-containing materials

CHAPTER 32

# Acid Soils

**Rivka Fidel**

## Learning Objectives

- Explain how soil **acidification** occurs naturally
- Describe how human activities contribute to soil acidification
- Explain how aluminum contributes to soil acidity and how it affects plant growth
- State the optimal pH range for plant growth and why

**Keywords**: pH in soil, acid soils, acidification

## A Closer Look at pH

You may have learned elsewhere that **acidic** solutions and soils have a pH < 7, and **basic** or **alkaline** solutions and soils have a pH > 7. Now consider that **pH** is calculated as:

$$pH = -log[H^+]$$

Thus, pH is the negative log of the hydrogen ion concentration. This means that as the $H^+$ concentration increases, pH decreases. Hence an acid soil has more $H^+$ ions than an alkaline soil. Additionally, the logarithmic scale of pH means each pH unit has 10x fewer $H^+$ ions than the last. In other words, a solution with pH 8 has $1/10^{th}$ the hydrogen ions than a solution with pH 7. And, a solution with pH 5 has 10x more hydrogen ions than a solution with pH 6.

## Soil Reaction Class pH's

Now, it's not just whether pH is greater than or less than 7 that matters to plants and soil organisms. When soil pH fits into more specific ranges, we start to see specific effects on soil processes, as well

as the growth of plants and microorganisms. For this reason, the USDA names specific soil pH ranges soil **reaction classes**. These reaction classes help us identify when plant growth limitations are likely.

| USDA Soil Reaction Class | pH range | Growth of average plants* |
|---|---|---|
| Ultra acidic | < 3.5 | Extremely limited |
| Extremely acidic | 3.5–4.4 | Very strongly limited |
| Very strongly acidic | 4.5–5.0 | Strongly limited |
| Strongly acidic | 5.1–5.5 | Moderately limited |
| Moderately acidic | 5.6–6.0 | Slightly limited |
| Slightly acidic | 6.1–6.5 | Not limited |
| Neutral | 6.6–7.3 | Not limited |
| Slightly alkaline | 7.4–7.8 | Slightly limited |
| Moderately alkaline | 7.9–8.4 | Moderately limited |
| Strongly alkaline | 8.5–9.0 | Strongly limited |
| Very strongly alkaline | > 9.0 | Very strongly limited |

**Estimated level of limitation to the growth of average plants is used here for conceptual purposes only (by Rivka Fidel, University of Arizona).*

As shown in the table, average plants grow best between pH 6.1–7.3. Other sources cite ranges of 6-7 or even 5.5–7.5, because the definition of an "average plant" varies. Many plants tolerate wide ranges of pH's, whereas others are more selective. Apple trees for example grow well from pH 5–7.5, whereas pomegranates are more sensitive and need pH 6–6.9. Even more narrow ranges such as 6–6.5 are frequently considered optimal for some agronomic crops like corn and wheat (see here for New York examples and here for Iowa examples [PDF, pg. 11]). Overall, plants tend to tolerate slightly acidic pH's better than slightly alkaline pHs. This is due to the effect of pH on nutrient availability.

## Problematic Acid Soils

Because most plants can slightly or even moderately acidic conditions well, here we will focus **problematic acid soils** – here defined as soils having a pH < 5.5 (i.e. strong acidity or greater). Below pH 5.5, plants are more likely to experience metal toxicity and/or nutrient deficiencies.

## How Problematic Acid Soils Develop

Acid soils, including problematic acid soils, develop through a process called **acidification**. During acidification, **acid cations** ($H^+$ and $Al^{3+}$) enter the soil and lower the soil pH. Concurrently, $H^+$ and $Al^{3+}$ in solution adsorb to soil surfaces, replacing the **nonacid cations** there.

Acid cations (mainly $H^+$) can come from outside the soil as inputs, or from chemical reactions occurring in soil. There are 5 main soil acidification processes, of which the first two are natural:

- Organism Metabolism
- Chemical weathering and decomposition
- Acid rain from fossil fuel combustion
- Excess $CO_2$, also from fossil fuel combustion
- Excavation of S-rich sediments
- Fertilizer addition

## Natural Causes of Acidification

### Organism Metabolism

Organisms in soil produce both organic acids and carbon dioxide ($CO_2$) as part of their metabolic processes, both of which lower soil pH. Plant roots can produce both $H^+$ ions and organic acids to help them get nutrients from soil. The organic acids, primarily weak acids, donate $H^+$ to the soil and thereby lower the pH. Microbes additionally produce organic acids as byproducts of their metabolism, and/or to help them break down organic matter and/or minerals.

Plants roots and soil microbes both produce $CO_2$ as a byproduct of aerobic respiration. This $CO_2$ then reacts with water to produce carbonic acid in a process called the **carbonation reaction**:

$$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)}$$

Then the **carbonic acid** ($H_2CO_3$) dissociates, forming bicarbonate and $H^+$:

$$H_2CO_{3(aq)} \rightleftharpoons HCO_3^-{}_{(aq)} + H^+_{(aq)}$$

Finally the $H^+$ lowers the pH, acidifying the soil.

### Chemical Weathering and Organic Matter Decomposition

Oxidation reactions occurring naturally in soil frequently have $H^+$ in their products, and therefore lower soil pH over time. Specifically, most acidifying redox reactions feature $O_2$ as the oxidizing agent, and

accepts electrons from another element such as N, Fe, or S. For example, **nitrification** – a reaction where N gets oxidized and $O_2$ gets reduced – produces 2 $H^+$ ions per N oxidized:

$$NH_4^{+}{}_{(aq)} + 2O_{2(g)} \rightleftharpoons NO_3^{-}{}_{(aq)} + H_2O_{(l)} + 2H^{+}{}_{(aq)}$$

## Anthropogenic Causes of Acidification

Human activity lowers pH through various means, with most of the impacts occurring at the local to regional scale.

### Acid Rain

Of all of the anthropogenic acidification processes, acid rain has likely acidified the most soil total**. Acid rain** is rainfall having a pH of ~4-5. This is much lower than normal rain, which has a pH of ~5.5. Acid rain forms due to emissions of $SO_x$ and $NO_x$ gases arising during fossil fuel burning. $SO_x$ gases are $SO_2$ and $SO_3$; $NO_x$ gases are NO and $NO_2$. These gases react with $O_2$ and $H_2O$ in the atmosphere, forming sulfuric acid ($H_2SO_4$) and nitric acid ($HNO_3$), respectively.

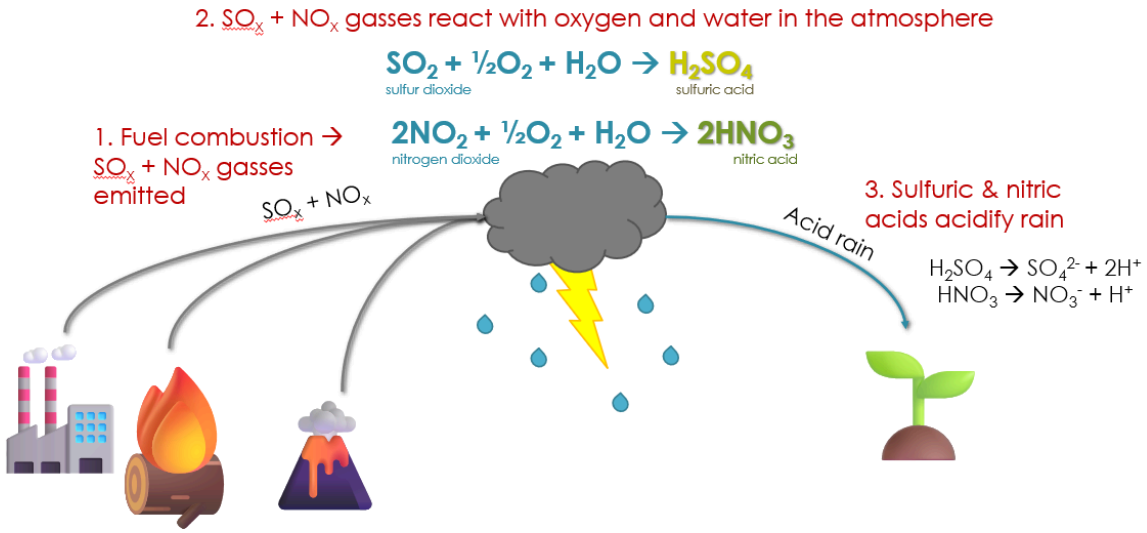



Diagram illustrating the process of acid rain. In modern times, $SO_x$ and $NO_x$ gases mainly come from the burning of fossil fuels, with a smaller contribution from wood fires, wildfires, and volcanoes (volcanoes specifically produce $SO_2$). Notice how acids are not present in the emissions themselves, but rather form in the atmosphere. Sulfur dioxide and nitrogen dioxide reactions with oxygen and water in the atmosphere are shown as examples because these are the most common types of $SO_x$ and $NO_x$ gases, respectively. [Image Credit: Rivka Fidel]

Among fossil fuels, coal – especially lignite coal – contains the most S, and hence produces the most $SO_2$ emissions. For this reason, regions downwind of coal-fired power plants tend to experience the most acid rain. For example, the Midwestern US has historically had the most coal-fired power plants. Before the Clean Air Act of 1970 (especially amendments made in 1990), the $SO_2$ from the power plants

caused the downwind Eastern Midwest and Northeastern US to experience especially acidic acid rain. Since then, the rain has become less acidic and less extensive, but still occurs to this day.

## Anthropogenic Carbon Dioxide Emissions

The burning of fossil fuels has raised $CO_2$ concentrations beyond what aerobic respiration alone could achieve, causing greater acidification than could be accounted for naturally. Indeed, current $CO_2$ concentrations of 410-420 ppm in 2025 are almost double the pre-industrial concentrations of ~280 ppm. This additional $CO_2$ lowers the pH of water, and hence soil, in the same manner as $CO_2$ from anywhere else: through the **carbonation reaction** (see above). However, because carbonic acid is a weak acid, it cannot lower the pH of rainfall below 5 like acid rain can. Hence it does *not* cause as much acidification as acid rain.

## Excavation & Exposure of S-Rich Soils & Sediments

So-called "reduced forms" of sulfur – $S^0$ , $S_2^{2-}$, and $S^{2-}$ – are found in wetland soils and deep within the Earth. When wetland soils are drained for construction or agriculture, $O_2$ gas enters the soil and elemental sulfur ($S^0$) and sulfide ($S^{2-}$) that naturally occur in the soil will readily react with the $O_2$ to form sulfuric acid ($H_2SO_4$). When rocks and sediments bearing "reduced" sulfur forms are excavated during mining, the same reactions occur after they reach the surface and encounter $O_2$ gas. Here are two example reactions:

$$S^0_{(s)} + 1.5O_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2SO_4^-{}_{(aq)}$$

$$S_2^{2-}{}_{(aq)} + 3.5O_{2(g)} + H_2O_{(l)} \rightleftharpoons H_2SO_4^-{}_{(aq)} + SO_4^{2-}{}_{(aq)}$$

Because $H_2SO_4$ is a strong acid, it dissociates immediately *and does not re-form*:

$$H_2SO_4^-{}_{(aq)} \rightleftharpoons 2H^+_{(aq)} + SO_4^{2-}{}_{(aq)}$$

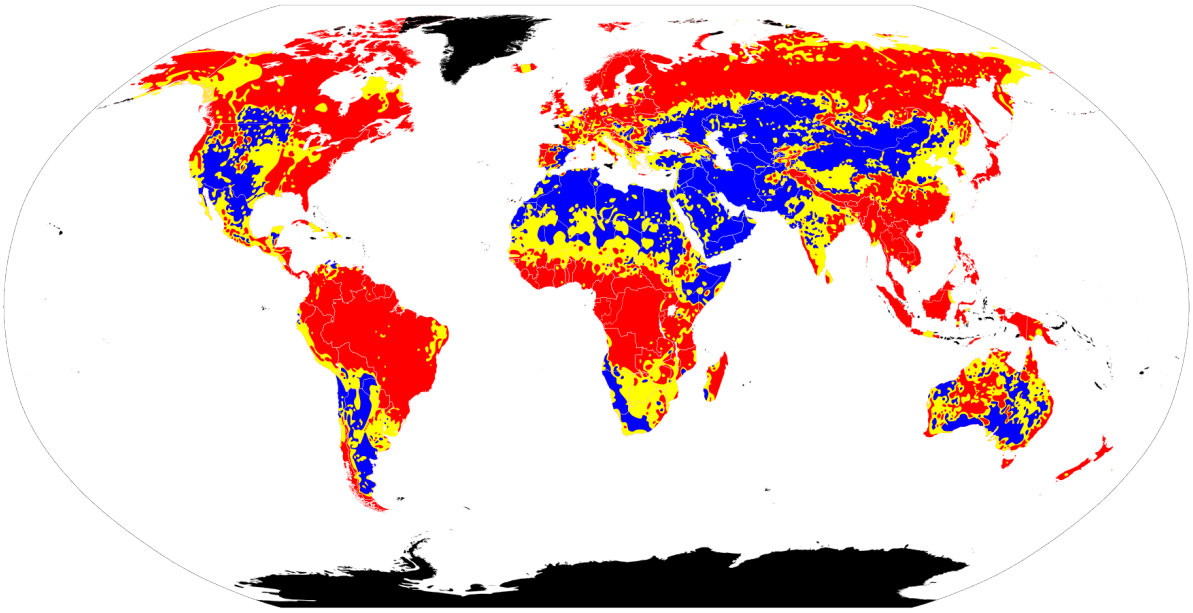
This raises the $[H^+]$ of the soil and lowers the pH.

## Addition of Fertilizers

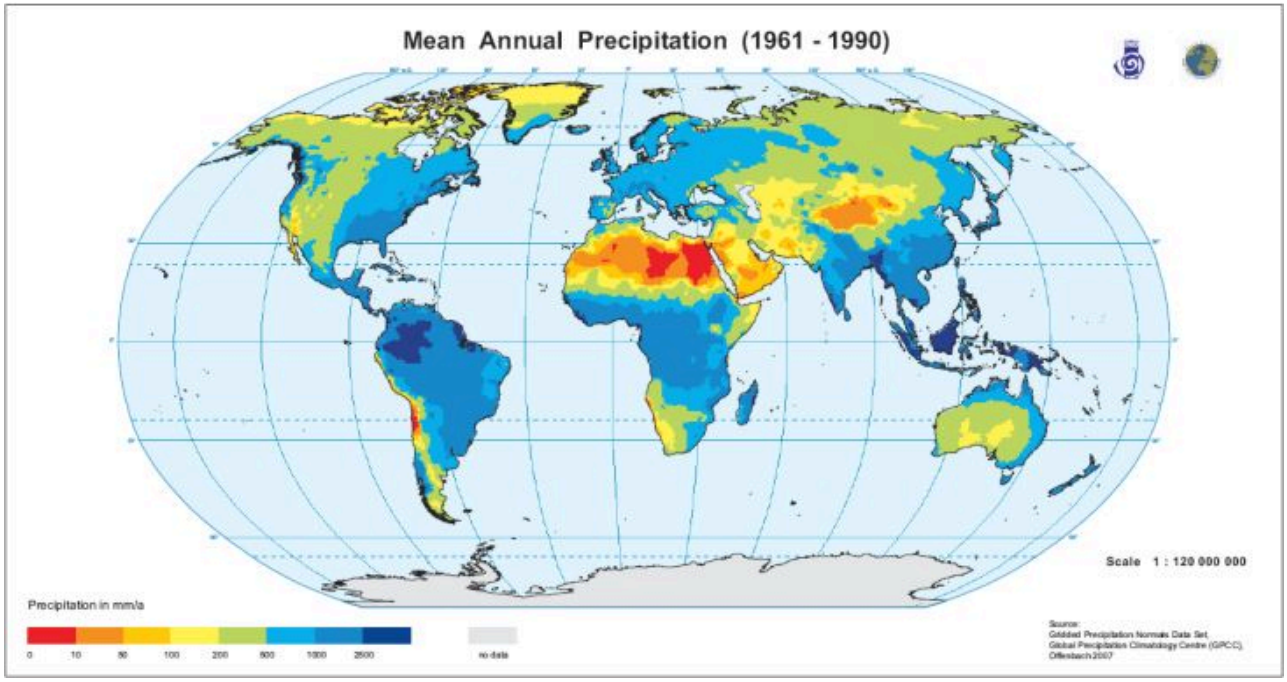
Some fertilizers are capable of donating electrons through oxidation reactions that yield $H^+$, and thereby cause acidification over time. For example, ammonium ($NH_4^+$) is a popular nitrogen fertilizer that causes acidification through the aforementioned **nitrification** reaction. Adding S fertilizers containing $S^0$ or $S^{2-}$ will likewise cause acidification when the S is oxidized and becomes sulfuric acid ($H_2SO_4$), per the above S oxidation reactions.

## Where are Acid Soils Found?

Of the aforementioned acidifying processes, naturally occurring carbonation reactions and chemical weathering are by far the most widespread. Since these both occur faster in soils with sufficient moisture, and rain itself is acidic (even without human influence), we would expect soils in wetter environments to be more acidic. And indeed, the below soil pH and precipitation maps together show this is generally true.



Global variation in soil pH. **Red** = acidic soil. **Yellow**= neutral soil. **Blue** = alkaline soil. **Black** = no data. [Image Credit: Soil pH | Ninjatacoshell | CC BY-SA 3.0]




Map of global precipitation. Red and orange indicate low precipitation; Blue indicates high precipitation [Image Credit: SERC].

Moreover, when there is sufficient rainfall, more trees can grow, further acidifying the soil via the addition of $H^+$ ions, $CO_2$, and organic acids from their roots. As we learned in earlier chapters, conifers especially produce copious acids from their roots, and also have the most acidic leaves when compared with grasses and broadleaf trees. Hence, coniferous forests are the most acidic, followed by broadleaf forests, and then grasslands. Wetter forests such as rainforests also tend to be more acidic, as do peatlands. Local-scale impacts, as would be expected for peatlands and mine sites, are not easily discernable on global maps, but are nonetheless important.

## Limits to Plant Growth in Acid Soils

Soil pH primarily affects plant growth through its effect on nutrient availability. Only nutrients that located in the soil solution or adsorbed to exchange sites are available to plants. So, anything that increases nutrients' solubility or the soil's exchange capacity will also influence availability.

### Metal Toxicities

Generally, **transition metal micronutrients** such as Fe, Mn, Cu, and Zn are more soluble at low pH's, and may reach toxic concentrations. This is because they normally bond to alkaline anions like $OH^-$ and $O^{2-}$, which have lower concentrations at low pH's. When pH decreases, the oxide and hydroxide anions react with $H^+$ to form water, making metal oxides and hydroxides more soluble. When pH falls

below 5.5, transition metal micronutrients can reach toxic concentrations, essentially causing plants to "overdose" on these micronutrients.

Problematic acid soils (pH<5.5), also often contain toxic concentrations of $Al^{3+}$. Al is a post-transition metal, and like transition metals, $Al^{3+}$ is more soluble at lower pHs. However, Al is not a plant nutrient, but instead is toxic to plants. Thus when pH falls below 5.5, plants commonly experience **aluminum toxicity**.

### More about Aluminum and Iron in Acid Soils

In addition to $H^+$, aluminum III ($Al^{3+}$) and iron ($Fe^{2+}$ and $Fe^{3+}$) are *also* **acid cations** because they undergo a type of reaction called **hydrolysis**. In hydrolysis, a metal accepts $OH^-$ from $H_2O$, leaving behind $H^+$ (see the acid and base saturation chapter for more information). For example, this is the aluminum hydrolysis reaction:

$$Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightleftharpoons Al(OH)_{3(s)} + 3H^+_{(aq)}$$

In problematic acid soils (pH<5.5), the abundance of $H^+$ (and lack of $OH^-$) helps *reverse* the aluminum hydrolysis reaction, favoring $Al^{3+}$ dissolution, and causing $Al^{3+}$ concentrations in solution to increase:

$$Al(OH)_{3(s)} + 3H^+_{(aq)} \rightleftharpoons Al^{3+}_{(aq)} + 3H_2O_{(l)}$$

Likewise, the iron II & III hydrolysis reactions also reverse easily when pH < 5.5, causing Fe ion concentrations in solution to increase:

$$Fe(OH)_{2(s)} + 2H^+_{(aq)} \rightleftharpoons Fe^{2+}_{(aq)} + 2H_2O_{(l)}$$

$$Fe(OH)_{3(s)} + 3H^+_{(aq)} \rightleftharpoons Fe^{3+}_{(aq)} + 3H_2O_{(l)}$$

$Fe^{2+}$ and $Fe^{3+}$ are far less abundant in the solution compared with $Al^{3+}$, so for practical purposes, scientists and growers normally focus on $H^+$ and $Al^{3+}$.

## Nutrient Deficiencies and Low CEC

Recall that CEC declines with declining pH, lowering the capacity of soil to adsorb and retain nutrients. This means that exchangeable nutrient cations like $Ca^{2+}$, $Mg^{2+}$, and $K^+$ are not retained well over time in acid soils, and instead leach out. Therefore, acid soils (especially when pH < 5.5) easily become deficient in these nutrients.

Additionally, the abundant $Al^{3+}$, $Fe^{2+}$ and $Fe^{3+}$ found in solution when pH < 5.5 easily bond to and

precipitate with phosphates ($H_2PO_4^-$, $HPO_4^{2-}$, $PO_4^{3-}$) and reducing plant-available P. Here are some example reactions:

- *Aluminum hydroxy phosphate* precipitation: $Al^{3+}_{(aq)} + H_2PO_4^-{}_{(aq)} + 2H_2O_{(l)} \rightleftharpoons 2H^+_{(aq)} + Al(OH)_2H_2PO_{4(s)}$
- *Variscite* precipitation: $Al^{3+}_{(aq)} + PO_4^{3-}{}_{(aq)} + 2H_2O_{(l)} \rightleftharpoons AlPO_4{\cdot}2H_2O_{(s)}$
- *Strengite* precipitation: $Fe^{3+}_{(aq)} + PO_4^{3-}{}_{(aq)} + 2H_2O_{(l)} \rightleftharpoons FePO_4{\cdot}2H_2O_{(s)}$

The solids in the products of these reactions are only poorly to slightly soluble. As a result, phosphorous availability decreases below pH 6.

At especially low pH's, normally below 5, sulfur may also become deficient. This is because when sufficient positive charge develops on colloid surfaces, $SO_4^{2-}$ can start adsorbing to positive charge sites through inner-sphere adsorption mechanisms. Meaning, $SO_4^{2-}$ becomes very strongly bound to the surfaces, making it non-exchangeable, and no longer plant-available.

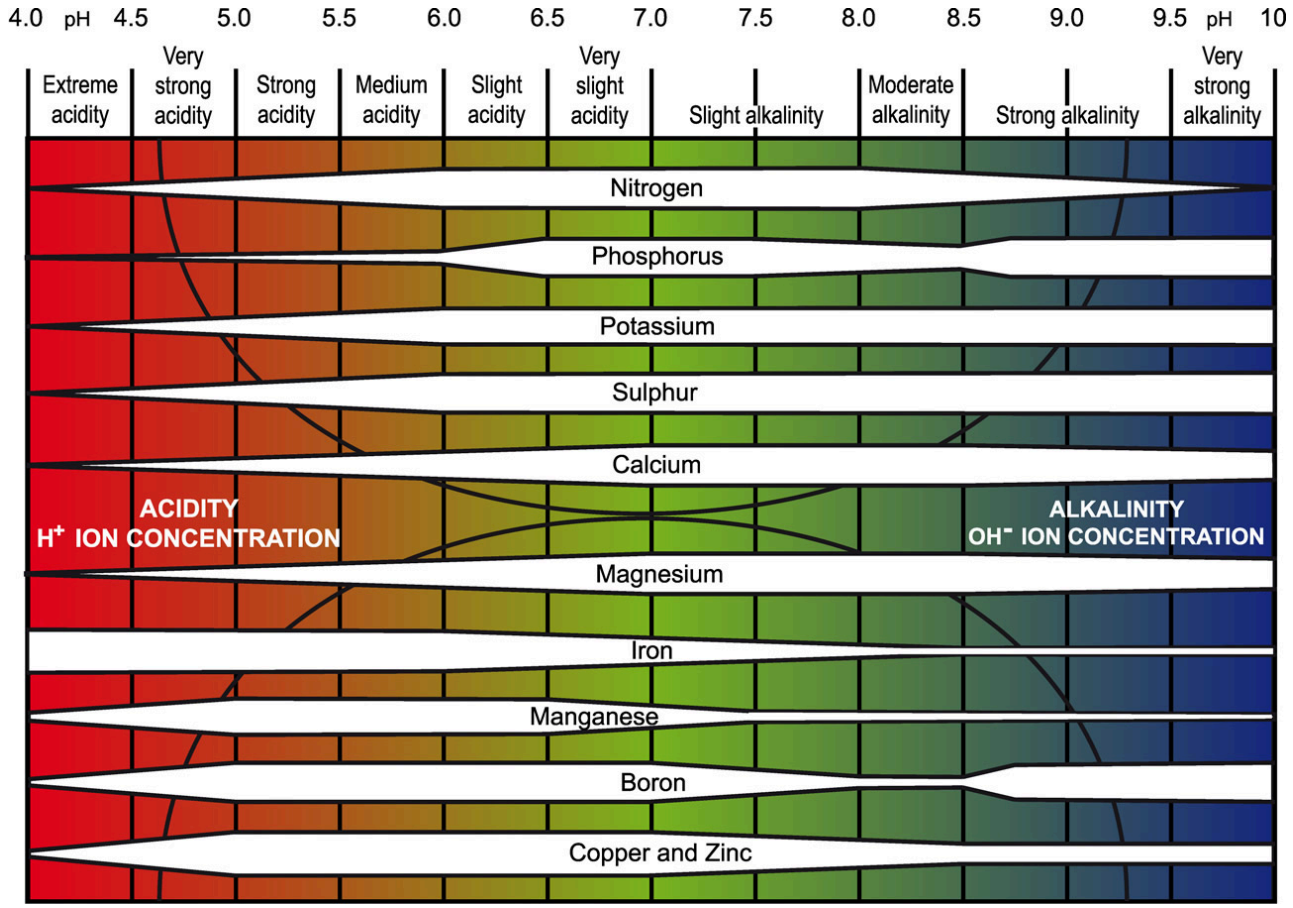



Figure showing pH influence on plant nutrient availability. [Image Credit: Potash Development Association]

This table shows at about what pH deficiencies are likely to occur, and other conditions under which deficiencies become more likely *(Data compiled by Jim Walworth, University of Arizona)*:

| Nutrient problem | Soil pH | Other soil conditions |
|---|---|---|
| Al and Mn toxicity | < 5.0 to 5.5 | depends on plant species and variety |
| Ca deficiency | < 4.5 to 4.8 | low CEC, tropical highly weathered soils |
| Mg deficiency | < 5.5 | low CEC or BS |
| Mo deficiency | < 5.5 | low solubility |
| N deficiency | < 5.0 to 5.5 | decreased nitrification & mineralization, low OM soils |
| P deficiency | < 5.0 | highly weathered soils, dominant in Al/Fe oxides |
| K deficiency | < 5.0 | low CEC, low BS, highly leached soils, high exchangeable Al |

**Legend:**

- CEC = Cation Exchange Capacity
- BS = Base Saturation *(see cation saturation percentages chapter)*
- OM = Organic Matter

## Summary of Problematic Acid Soil Plant Impacts

To summarize, problematic acid soils (pH < 5.5) limit plant growth as follows:

- Aluminum toxicity due to enhanced solubility of $Al^{3+}$
- Excess available transition metal micronutrients *(often reaching toxic levels)*: $Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$ and $Zn^{2+}$
- Low cationic macronutrients: $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$
- Low plant-available P due to $PO_4^{3-}$ precipitating with Al and Fe

## Key Takeaways

Note the following about acid soils and acidification

- Distinguishing property: Low pH (excessive $H^+$)
    - **Acid soil:** pH < 7
    - **Problematic acid soil:** pH < 5.5
- Formation conditions
    - Acid soils are found in moist climates on the global scale, because rain accelerates acidification
    - **Acidification** is the accumulation of $H^+$ in the soil. There are several processes that acidify soil:
        - Organism Metabolism
        - Chemical weathering and decomposition
        - Acid rain from fossil fuel combustion
        - Excess $CO_2$, also from fossil fuel combustion
        - Excavation of S-rich sediments
        - Fertilizer addition
- **Problematic acid soils** (pH < 5.5) limit plant growth as follows:
    - Low cation macronutrients: $Ca^{2+}$, $Mg^{2+}$, and $K^+$
    - High transition metal micronutrients (often reaching toxic levels): $Fe^{2+}$, $Mn^{2+}$ and $Cu^{2+}$
    - Low P due to $PO_4^{3-}$ precipitating with Al and Fe
    - Aluminum toxicity due to enhanced solubility of $Al^{3+}$

CHAPTER 33

# Alkaline Soils

**Rivka Fidel**

## Learning Objectives

- Identify common alkalis from a list of compounds found in soil
- Explain how and where alkaline soils form
- Describe how calcite-carbonate/rich soils are identified
- Explain which nutrients are frequently deficient in alkaline soils and why
- Explain why isn't it economical to remediate alkaline soils in the field
- Describe how small quantities of alkaline soil (ex: in pots and raised beds) can be remediated
- List appropriate soil acidifiers for lowering soil pH

**Keywords**: alkaline soil, alkali, calcareous soil, calcic horizon, calcite, carbonate

## What is an alkaline soil?

In a chemical sense, **alkaline soils** simply have pH > 7, just like ordinary basic solutions. Recall that $pH = -log[H^+]$, so alkaline soils have low $[H^+]$, and consequently more $OH^-$ than $H^+$. The more $OH^-$ (and less $H^+$) a soil has, the greater its alkalinity.

## What are alkalis?

**Alkalis** are basic salts that include an alkali or alkaline earth metal. Recall that bases accept $H^+$ and thereby raise the pH. Salts are all ionic solids, composed of a metal cation and nonmetal anion. Therefore, we can also define alkalis as containing an alkali or alkaline earth metal, plus an anion that acts as a base. Here are some examples of alkalis and the ions that form when they dissolve:

| Alkali | Metal cation(s) | Nonmetal anion(s) (base(s)) |
|---|---|---|
| NaOH | $Na^+$ | $OH^-$ |
| $Ca_5(PO_4)_3(OH)$ | $Ca^{2+}$ | $PO_4^{3-}$ and $OH^-$ |
| $CaCO_3$ | $Ca^{2+}$ | $CO_3^{2-}$ |
| $Ca,Mg(CO_3)_2$ | $Ca^{2+}$ and $Mg^{2+}$ | $CO_3^{2-}$ |

Note that the metals in alkalis are all **nonacid cations**. Unlike $Al^{3+}$ and transition metals, these are *not* capable of accepting $OH^-$ (this is why NaOH completely dissociates in water and does not re-form). The most common nonacid cation in soil is $Ca^{2+}$, followed by $Mg^{2+}$, $K^+$, and $Na^+$. The most common alkaline (basic) anion in soil, by far, is $CO_3^{2-}$. Consequently, the most common alkali in soil is **calcite** ($CaCO_3$).

## How do alkaline soils develop?

Alkaline soils develop primarily in arid to semi-arid regions, as well as poorly drained areas, due to the lack of $H^+$ additions from rain and/or also lack of alkali losses through leaching. When there is insufficient water flow to wash away alkalis, and insufficient acid to neutralize them, they accumulate in soil. Over time, these alkalis – primarily calcite – reach a sufficiently high concentration to increase the pH above 7.4, where we start seeing negative effects on average plants.

When calcite specifically accumulates, the resulting soils are called **calcareous**. Calcareous soils are very common in deserts wherever soil has had sufficient time to develop, and can also be found in areas experiencing dry winters and/or summers such as grasslands and Mediterranean shrublands. In the case of moist grasslands like in the Midwest, calcareous soils are commonly found low in the landscape, where the soil is poorly drained and receives dissolved or eroded carbonate minerals from upslope. During dry periods, the carbonate-rich water evaporates, leaving behind calcite and smaller amounts of other carbonate salts.

Calcareous soils also commonly develop from limestone or other carbonate-rich parent materials. In these soils, the topsoil grows more acidic over time, but the subsoil remains alkaline and calcareous. Then, when erosion carries away the more acidic topsoil, it may expose calcite-rich layers of soil or sediment at the surface.

Many calcareous soils have **calcic horizons** where calcite has accumulated over time in the subsoil (endopedon). Calcareous soils and calcic horizons can be identified using **effervescence** testing. Over time calcic horizons can become cemented as the calcite fills in the pores between particles, turning them into **petrocalcic horizons**.



This soil in NE Kansas shows calcium carbonate accumulation lower in the profile, shown by the white masses. [Photo Credit: Amber Anderson]



This soil near North Platte, NE, shows a calcium carbonate 'rind' on the soil due to a lack of leaching in loess materials. [Photo Credit: Amber Anderson]



This petrocalcic, cemented horizon due to calcium carbonate is present in this Southern California aridisol from 35-80 cm. [Photo Credit: Amber Anderson]



This soil in Iowa shows a clear development line approximately 2/3 down the profile. Material below this(lighter colored) is calcareous due to the parent material having free calcium carbonate, and a lack of development as the soil is too young. [Photo Credit: Amber Anderson]

## Identifying Calcareous Soils: Effervescence Test

Calcite-rich soils and soils rich in other carbonates such as $Na_2CO_3$ can be identified using **effervescence** testing. To perform the test, simply add a few drops of 1 M HCl and watch for bubbles. More bubbles indicate more carbonates.

This table shows the different effervescence classes and their criteria (NRCS):

| Effervescence Class Terms | Abbreviation | Effervescence class Criteria |
|---|---|---|
| Non-effervescent | NE | No bubbles form |
| Very slightly effervescent | VS | Few bubbles form |
| Slightly effervescent | SL | Numerous bubbles form |
| Strongly effervescent | SE | Bubbles form a low foam |
| Violently effervescent | VE | Bubbles quickly form a thick foam |

The following reaction is responsible for the bubbles (the ↑ indicates gas escaping and bubbling):

$$CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2\uparrow$$

Calcareous soils will bubble upon adding other acids as well, such as acetic acid, which is found in vinegar. However, vinegar isn't strong enough to react with some of the less calcareous soils – in other words, it cannot detect low concentrations of carbonate salts. You can use it for at-home testing – handy when children/pets are present – but interpret results cautiously. Fewer bubbles are expected when using vinegar compared with HCl.

Similar to soil scientists, geologists use HCl to identify calcite and limestone specimens, but the test is normally used non-quantitatively in geology to simply indicate the presence or absence of carbonates.

Normally calcareous soils have a pH between ~7.5-8.5, no matter how much calcite has accumulated. This is because calcite is poorly soluble in neutral to alkaline water. Therefore, the low solubility of calcite limits the concentration of $CO_3^{2-}$ in the soil solution. However, in the salt-affected soils chapter, we'll learn that the presence of excess sodium in alkaline soils increases the solubility of $CO_3^{2-}$, allowing the pH to rise above 8.5.

## When and why is soil alkalinity problematic for plants?

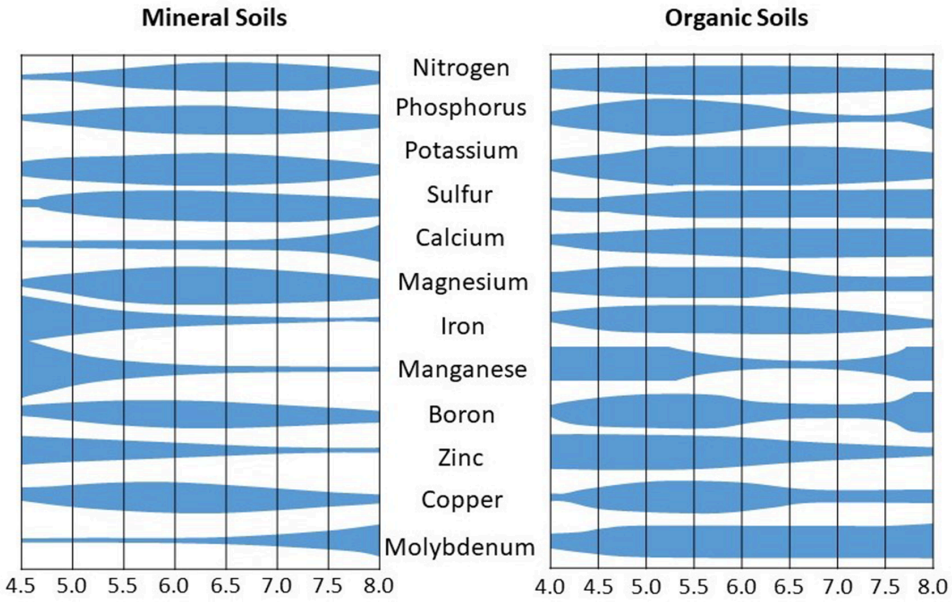
As with acidity, some plants are more sensitive to alkalinity than others, so it is hard to generalize impacts of alkalinity on all plants. From the reaction classes table in the acid soils chapter, you may have noticed that slightly alkaline soils (pH 7.4-7.8) have slight limitations to plant growth, moderately alkaline soils (pH 7.9-8.4) have moderate limitations to plant growth, and so forth. Soil pH can only exceed 8.5 when excess sodium is present; see information on sodic soils in the salt-affected soils chapter.

| Alkaline soil-intolerant crop examples | Slightly alkaline soil–tolerant crop examples | Alkaline soil–tolerant crop examples |
|---|---|---|
| • Azalea<br>• Blueberries<br>• Cassava<br>• Coffee<br>• Corn *(typical cultivars)*<br>• Cranberries<br>• Potatoes<br>• Soybeans<br>• Tea | • Barley<br>• Cabbage & other brassicas<br>• Carrots<br>• Cotton<br>• Corn *(select cultivars only)*<br>• Oats<br>• Lettuce<br>• Peas<br>• Rice<br>• Spinach<br>• Wheat | • Alfalfa<br>• Asparagus<br>• Barley<br>• Cantaloupe<br>• Dates<br>• Grapes<br>• Pecans<br>• Walnuts |

If we examine the plant nutrient availability diagram, we can see that the plant-availability of **transition metal micronutrients** starts declining above pH 7. The rate of decline is fastest in manganese (Mn), followed by iron (Fe), then copper (Cu) and zinc (Zn). So, we would expect that as pH increases, Mn deficiencies would occur first, then Fe deficiencies, and then Cu and Zn.

Most nutrient availability diagrams are generalized to all soil types, but most of the more alkaline soils are found in dry regions for the aforementioned reasons, and such soils are generally low in organic matter. Therefore, we've included an alternative set of nutrient availability diagrams below (different from the one appearing in the acid soils chapter), which show the difference between mineral vs organic soils. Outside of wetland soils, the mineral soils diagram on the left is most appropriate. The reason organic matter affects nutrient availability is because nutrients adsorb to organic matter at different pH's compared to minerals due to its different surface chemistry. Likewise, among mineral soils, the minerology affects both the rate of nutrient sorption and precipitation of nutrients with other ions. Generally such diagrams should be interpreted cautiously since the actual effect of pH on soil

nutrient availability depends on the minerology of the soil as well as the organic matter content and composition.




Nutrient availability in mineral and organic soils influenced by soil pH. [Image Source: Adapted for *Digging Into Canadian Soils* from Munroe (2018) by Lewis Fausak, CC BY 4.0.]

To summarize, alkaline soils present the following challenges to plant growth:

- Low transition metal micronutrient availability: $Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$, and $Zn^{2+}$
  - Largely due to hydrolysis, i.e. precipitation with $OH^-$
- Low P availability
  - Largely due to $PO_4^{3-}$ precipitation with $Ca^{2+}$ and $Mg^{2+}$

## Can we remediate alkaline soils?

### Not in the field!

It is *not* normally economical to acidify alkaline soils *in situ*, i.e. the field. This is because alkaline soils (especially calcareous ones) tend to contain enormous amounts of calcite, and each mole of calcite ($CaCO_3$) requires 2 moles of $H^+$ to neutralize it. Furthermore, even if you acidify the topsoil, the subsoil will likely have even more calcite in it that may eventually move upwards as the groundwater table rises and falls.

## Estimating Acid Requirement for an Alkaline Soil *in Situ* (in the field)

Consider 1 ha of soil with just 1% $CaCO_3$ in the top 30 cm of soil. How much $CaCO_3$ would it contain in total and how much $H_2SO_4$ would be needed to neutralize it? Assuming an average bulk density of 1.3 g/cm$^3$, we need to first calculate how much $CaCO_3$ it would have (1 Mg = 1 metric ton = $10^3$ kg = $10^6$ g) using unit conversions (highlights show cancelling units):

$$30cm * \frac{10^8 cm^2}{1ha} * \frac{1.3g\ soil}{cm^3\ soil} * \frac{1Mg\ soil}{10^6 g\ soil} * \frac{1Mg\ CaCO_3}{100Mg\ soil}$$

*=39 Mg $CaCO_3$/ha*

…and then use mole-mass ratios to determine how much sulfuric acid would be required to neutralize it (each mole of $H_2SO_4$ has 2 $H^+$ so we don't need to multiply by 2):

$$\frac{39Mg\ CaCO_3}{ha} * \frac{1\ mol}{100g\ CaCO_3} * \frac{98g\ H_2SO_4}{1mol}$$

*=38 Mg $H_2SO_4$/ha*

These calculations don't account for leaching losses, or how diluted $H_2SO_4$ has to be before it can be safely applied to soil. So, you'd have to apply *even more* $H_2SO_4$ solution compared with what we just calculated here. At the time of writing (2025), 0.725 Mg of technical grade sulfuric acid costs ~$1,000 (or more). Thus, even without accounting for leaching losses or dilution, you'd have to spend *over $50,000 per hectare!*

What if you want to add elemental S instead? Then less is needed since S weighs less, and 1 mol of S produces 1 mol of $H_2SO_4$ after reacting with $O_2$ (see reactions in the below section).

$$\frac{39Mg\ CaCO_3}{ha} * \frac{1\ mol}{100g\ CaCO_3} * \frac{32g\S}{1mol}$$

*= 12.5 Mg S /ha*

At the time of writing, you can buy 2000 lbs (0.907 Mg) of elemental S for $845. So, 12.5 Mg ÷ 0.907 Mg × $845 = $11,645. Even if you were to find a bulk discount, the costs would easily exceed $10k per hectare.

As you can see, the costs of acidifying soil *in situ* add up quickly, no matter what acidifying agent you use. Therefore it is normally not feasible to acidify alkaline soil to pH's suitable for average crops (i.e. pH 7 or less) in the field.

## …But we can acidify pots and raised beds

As a result of calcite chemistry and the enormous amounts of it in alkaline soils, it is only economical to acidify very small amounts of soil such as pots of soil or raised beds filled with soil. To lower the pH of small amounts of alkaline soil, the following can be added:

- Sulfuric acid: $H_2SO_4$
- Elemental sulfur: $S^0$
- Acidic metal compounds: $Al_2(SO_4)_3$ and $FeSO_4$

Elemental sulfur and the acidic metal compounds do not themselves contain $H^+$; instead a preliminary reaction in soil must occur first before the pH decreases. As a result, these latter two will lower the soil pH more slowly. The acid-generating reactions for these amendments are shown in the below table (the $Al_2(SO_4)_3$ and $FeSO_4$ are assumed to dissolve rapidly, so that the vast majority of the acid cations, $Al^{3+}$ and $Fe^{2+}$, end up dissolving).

| Soil acidifier | Acid-generating reaction in soil |
|---|---|
| $S^0$ | $S^0_{(s)} + 1.5O2_{(g)} + H_2O_{(l)} \rightleftharpoons H_2SO_{4(aq)}$ |
| $Al_2(SO_4)_3$ | $Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightleftharpoons Al(OH)_{3(s)} + 3H^+_{(aq)}$ |
| $FeSO_4$ | $Fe^{2+}_{(aq)} + 2H_2O_{(l)} \rightleftharpoons Fe(OH)_{2(s)} + 2H^+_{(aq)}$ |

Elemental sulfur in particular requires a biologically-mediated redox reaction to acidify soil (the first reaction in the above table), and is known to frequently take a long time to lower the pH, especially in dry conditions. Its acidification rate is furthermore variable, depending on the weather and abundance of S-oxidizing microorganisms. Consequently, when at first the pH doesn't go down sufficiently after $S^0$ addition, it is best to wait longer for results, so as to avoid overshooting and accidentally over-acidifying the soil. Nonetheless, elemental S is relatively inexpensive and safe to use, with a minimal risk of adding excess Al or Fe, making it the most popular soil acidifier.

### Calculating elemental S to add to alkaline soil in a raised bed

Let's say you need to acidify an alkaline soil in a raised bed that is $1m^3$ in volume, and the soil has a bulk density of $1.2\ g/cm^3$. If the % carbonate or calcite is unknown, we can use effervescence to get a very approximate estimate following Maschmedt 2004.

| Effervescence Class Terms | Abbreviation | Effervescence class Criteria | Approximate % carbonate |
|---|---|---|---|
| Non-effervescent | NE | No bubbles form | <0.5 |
| Very slightly effervescent | VS | Few bubbles form | 0.5-1.5 |
| Slightly effervescent | SL | Numerous bubbles form | 1.5-8 |
| Strongly effervescent | SE | Bubbles form a low foam | 1.5-8 |
| Violently effervescent | VE | Bubbles quickly form a thick foam | >8 |

Let's say the soil was very slightly effervescent (VS), so for simplicity we'll assume **~1%** calcite from the table above. As with soil in the field, we need to calculate the mass of calcite (the term ***1 g $CaCO_3$/100g soil*** is equivalent to **1%** calcite):

$$\frac{1\text{m}^3}{1\text{ bed}} \times \frac{100^3\text{cm}^3}{1\text{m}^3} \times \frac{1.2\text{g soil}}{1\text{cm}^3} \times \frac{1\text{g CaCO}_3}{100\text{g soil}} \times \frac{1\text{kg}}{1000\text{g}}$$

***=12 kg/bed***

Now we use mass-mole ratios to calculate the elemental S to add:

$$\frac{12\text{kg CaCO}_3}{\text{bed}} \times \frac{1\text{mol}}{100\text{g CaCO}_3} \times \frac{32\text{g S}^0}{1\text{mol}}$$

***=3.8 kg S/bed***

Prices for gardening-sized bags of elemental S vary but if we assume ~$1-2/lb ($0.5-1/kg) based on prices of 50 lb bags in 2025, then this would cost $2-4.

So we see that, in contrast to acidifying many acres or hectares of soil in the field, lowering the pH of alkaline soil in raised beds or pots can be relatively affordable.

## Key Takeaways

- Alkaline soils have pH > 7 because they have more $OH^-$ than $H^+$
- Alkaline soils gradually become more problematic to plant growth as pH rises; the degree of effect depends on the plant in question
- The most common alkali in soils is $CaCO_3$, **calcite**
- **Effervescence** testing (adding acid and watching for bubbles) is used to test for calcite and other carbonates
- Alkaline soils present the following challenges to plant growth:
    - Low transition metal micronutrient availability: $Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$, and $Zn^{2+}$
        - Largely due to hydrolysis, i.e. precipitation with $OH^-$
    - Low P availability
        - Largely due to $PO_4^{3-}$ precipitation with $Ca^{2+}$ and $Mg^{2+}$
- It is *not* usually economical to lower the pH of alkaline soils in the field
- The following soil acidifiers can be used to lower pH of alkaline soil in pots, raised beds, and other containers: $H_2SO_4$, $S^0$, $Al_2(SO_4)_3$, and $FeSO_4$

CHAPTER 34

# Cation Saturation Percentages

**Rivka Fidel**

## Learning Objectives

- Define **cation saturation percentage**
- Define and calculate:
  - **Acid saturation**
  - **Base saturation**
  - **Exchangeable sodium percentage***

**Content for this learning objective is continued in the salt-affected soils chapter.*

**Keywords**: cation saturation percentage, acid saturation, base saturation

A **cation saturation percentage** is simply the percentage of a specific exchangeable cation out of the total exchangeable cations. Here we will mainly discuss **acid saturation** and **nonacid saturation**. Because *exchangeable sodium percentage* is discussed in the salt-affected soils chapter, only the formula is provided here.

## Acid vs. Nonacid Cations

Before calculating acid saturation and nonacid saturation, we must first identify the acid cations and nonacid cations. **Acid cations** are positively charged ions that lower pH, namely $H^+$ and $Al^{3+}$. **Nonacid cations** are positively charged ions that do not have a significant effect on pH (these are also called "base cations", but they are not bases). The most common nonacid cations in soil are $Na^+$, $K^+$, $Mg^{2+}$ and $Ca^{2+}$.

| Acid cations in soil | Nonacid cations in soil ("base cations") |
|---|---|
| $H^+$<br>$Al^{3+}$ | $Na^+$<br>$K^+$<br>$Mg^{2+}$<br>$Ca^{2+}$ |

### Why are Nonacid Cations Frequently Called "Base Cations"?

As the name implies, nonacid cations are not acids, but they are also not bases. So why are they often called "base cations"? The common "base cations" – $Na^+$, $K^+$, $Mg^{2+}$ and $Ca^{2+}$ – are alkali metals and alkaline earth metals, found in the first two columns of the periodic table. As a result, they tend to be found in alkalis such as $CaCO_3$. Because of this tendency to precipitate with basic anions like $CO_3^{2-}$, concentrations of these cations is correlated with the concentration of basic anions found in soil, and the nonacid cations were therefore frequently used as a *proxy* for basicity or alkalinity of soil.

## Acid Saturation

The **acid saturation (AS)** is the fraction of exchangeable acid cations out of the total exchangeable cations, in centimoles of charge per kilogram. Normally this is expressed as a percentage, so it can also be called **acid saturation percentage**. Since total exchangeable cations is the same as CEC, we write calculate the acid saturation as:

Units in both the numerator and denominator must be centimoles of charge per kilogram ($cmol_c/kg$), just like when calculating CEC.

$$AS = \frac{[H^+] + [Al^{3+}]}{CEC} = \frac{[H^+] + [Al^{3+}]}{[H^+] + [Al^{3+}] + [Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+]}$$

When calculating a percent, we can add "x100%" to the formula as a reminder to move the decimal twice to the right at the end:

$$\%AS = \frac{[H^+] + [Al^{3+}]}{CEC} \times 100\%$$

## Example %AS calculation

When we're given units in mg/kg, we first have to convert to $cmol_c$/kg. Let's say we have a soil with exchangeable cation concentrations as shown in the below table. For convenience, the cations' molar masses have also been added to the table, but these can easily be found in a periodic table.

| Cation | Concentration adsorbed to exchange sites (mg/kg) | Molar mass (mg/mmol) |
|---|---|---|
| $Ca^{2+}$ | 2200 | 40 |
| $Mg^{2+}$ | 800 | 24 |
| $K^{+}$ | 600 | 39 |
| $Na^{+}$ | 300 | 23 |
| $Al^{3+}$ | 200 | 27 |
| $H^{+}$ | 150 | 1 |

Now we'll convert the units for each cation:

$$\frac{2200\ mg\ Ca^{2+}}{kg\ soil} \times \frac{mmol}{40\ mg} \times \frac{cmol}{10\ mmol} \times \frac{2\ cmol_c}{cmol} = \frac{11\ cmol_c}{kg\ soil}$$

$$\frac{800\ mg\ Mg^{2+}}{kg\ soil} \times \frac{mmol}{24\ mg} \times \frac{cmol}{10\ mmol} \times \frac{2\ cmol_c}{cmol} = \frac{6.7\ cmol_c}{kg\ soil}$$

$$\frac{600\ mg\ K^{+}}{kg\ soil} \times \frac{mmol}{39\ mg} \times \frac{cmol}{10\ mmol} \times \frac{1\ cmol_c}{cmol} = \frac{1.5\ cmol_c}{kg\ soil}$$

$$\frac{300\ mg\ Na^{+}}{kg\ soil} \times \frac{mmol}{23\ mg} \times \frac{cmol}{10\ mmol} \times \frac{1\ cmol_c}{cmol} = \frac{1.3\ cmol_c}{kg\ soil}$$

$$\frac{200\ mg\ Al^{3+}}{kg\ soil} \times \frac{mmol}{27\ mg} \times \frac{cmol}{10\ mmol} \times \frac{3\ cmol_c}{cmol} = \frac{2.2\ cmol_c}{kg\ soil}$$

$$\frac{150\ mg\ H^{+}}{kg\ soil} \times \frac{mmol}{1\ mg} \times \frac{cmol}{10\ mmol} \times \frac{1\ cmol_c}{cmol} = \frac{15\ cmol_c}{kg\ soil}$$

Then add up the $cmol_c$/kg from all 5 cations, to get the CEC:

*11 $cmol_c$/kg +6.7 $cmol_c$/kg +1.5 $cmol_c$/kg +1.3 $cmol_c$/kg +2.2 $cmol_c$/kg +15 $cmol_c$/kg*

*=37.7 $cmol_c$/kg*

And finally divide the acid cations by the CEC:

$$AS = \frac{[H^{+}] + [Al^{3+}]}{CEC}$$

$$= \frac{2.2\ cmol_c/kg + 15\ cmol_c/kg}{37.7\ cmol_c/kg}$$

## Nonacid saturation

Mirroring acid saturation, **nonacid saturation (NS)** is the exchangeable nonacid cations out of the total exchangeable cations, in centimoles of charge per kilogram. Normally this is expressed as a percentage, so it can also be called **nonacid saturation percentage (%NS)**. It can also be called *base saturation* (BS) or *base saturation percentage* (%BS). To calculate it, we divide exchangeable nonacid cations by the CEC:

$$NS = BS = \frac{[Ca^{2+}] + [Mg^{2+}] + [K^{+}] + [Na^{+}]}{CEC}$$

Or as a %

$$\%NS = \%BS = \frac{[Ca^{2+}] + [Mg^{2+}] + [K^{+}] + [Na^{+}]}{CEC} \times 100\%$$

### Example %NS calculation

Using the same soil as the %AS calculation, before we found that the concentrations of the individual cations were:

| Exchangeable Cation | Concentration Adsorbed to exchange sites ($cmol_c/kg$) |
|---|---|
| $Ca^{2+}$ | 11.0 |
| $Mg^{2+}$ | 6.7 |
| $K^{+}$ | 1.5 |
| $Na^{+}$ | 1.3 |
| $Al^{3+}$ | 2.2 |
| $H^{+}$ | 15.0 |

Additionally, when we added up the $cmol_c/kg$ of all cations, we found that the CEC of the soil was 37.7 $cmol_c/kg$. So now we can calculate %NS:

$$NS = BS = \frac{[Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+]}{CEC}$$

$$= \frac{11 + 6.7 + 1.5 + 1.3}{37.7} = 0.54$$

=54%

## Exchangeable Sodium Percentage

**Exchangeable sodium percentage** is used to quantify sodicity, as explained in the salt-affected soils chapter. Notice how the formula is similar to the other cation saturation percentages, in that you divide the cation(s) of interest – here, just sodium – by the CEC.

$ESP = \frac{[Na^+]}{CEC} \times 100\%$ When abbreviated ESP, the "P" stand for percentage. Hence the "x100%" is simply a reminder to move the decimal twice to the right at the end, to convert from a fraction to percent.

### Key Takeaways

A **cation saturation percentage** is the % of exchange sites occupied by a certain type of cation. Here we've learned how to calculate 3 different cation saturation percentages.

- **Acid saturation** = fraction of surface exchange sites occupied by acid cations
  - as a fraction: $AS = \frac{[H^+] + [Al^{3+}]}{CEC}$
  - as a percent: $\%AS = \frac{[H^+] + [Al^{3+}]}{CEC} \times 100\%$
- **Nonacid saturation** = "base saturation" = fraction of surface exchange sites occupied by nonacid ("base") cations
  - as a fraction: $NS = BS = \frac{[Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+]}{CEC}$
  - as a percent: $\%NS = \%BS = \frac{[Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+]}{CEC} \times 100\%$

- **Exchangeable sodium percentage** = % of surface exchange sites occupied by sodium ions:

$$ESP = \frac{[Na^+]}{CEC} \times 100\%$$

CHAPTER 35

# Liming: Raising the pH of Acid Soils

**Rivka Fidel**

## Learning Objectives

Upon completing this chapter, you should be able to:

- Define **liming agent, agricultural lime, calcite,** and **dolomite**
- Identify liming agents from a list of materials
- Explain how calcite and similar liming agents raise the pH of acid soil
- Estimate liming requirements from soil texture and pH using a graph
- Calculate a soil's liming requirement using the acid saturation (%AS), CEC, volume ($V_s$), and bulk density ($D_b$) of the soil

**Keywords**: liming agents, agricultural lime, calcite, dolomite. liming requirements

## Liming

The pH of problematic acid soils (pH < 5.5) can be raised with alkaline materials called **liming agents**. The names "liming agent" and "agricultural lime" come from limestone, which is alkaline. Limestone is alkaline because it contains the base carbonate ($CO_3^{2-}$), found in two common limestone minerals: **calcite** ($CaCO_3$) and **dolomite** ($(Ca,Mg)CO_3$). The most common liming agent is **agricultural lime** , a ground-up limestone product rich in calcite and/or dolomite. Besides adding agricultural lime to raise pH, other alkaline substances can be added, including quicklime (CaO), wood ash, and slag leftover from fossil fuel combustion.

Liming agents are all alkalis (bases containing alkali metals and/or alkaline earth metals) that work by accepting $H^+$. For example, each mole of **carbonate** ($CO_3^{2-}$) from **calcite** ($CaCO_3$) can accept 2 moles of $H^+$ in an **acid-base reaction**:

$$CaCO_{3(s)} + 2H^+_{(aq)} \rightleftharpoons H_2CO_{3\ (aq)} + Ca^{2+}_{(aq)}$$

The carbonic acid then turns into $CO_2$ and $H_2O$ in a reaction called **decarbonation** (the reverse of carbonation):

$$H_2CO_{3(aq)} \rightleftharpoons \uparrow CO_{2(g)} + H_2O_{(l)}$$

Notice how the $CO_2$ is in the gas phase – this means it can easily escape the soil, decreasing the concentrations of the products in the soil and speeding up the reaction (aka "right shift") via *Le Chatelier's Principle*. Although largely beyond the scope of introductory soil science, briefly, *Le Chatelier's Principle* states that a chemical reaction experiencing a change in reactant or product concentrations (or temperature or pressure changes) will shift oppositely from the change, back towards equilibrium.

Meanwhile, the $Ca^{2+}$ ions do *not* directly raise the pH but rather help force more colloid-adsorbed $H^+$ into the solution:

$$H^+[Colloid]H^+ + Ca^{2+}_{(aq)} \rightleftharpoons [Colloid]Ca^{2+} + 2H^+_{(aq)}$$

Notice how one $Ca^{2+}$ from calcite replaces two $H^+$ on the colloidal surfaces to maintain equivalent charges. Similarly, 3 $Ca^{2+}$ ions from the solution replace 2 adsorbed $Al^{3+}$:

$$2[Colloid]Al^{3+} + 3Ca^{2+}_{(aq)} \rightleftharpoons 3[Colloid]Ca^{2+} + 2Al^{3+}_{(aq)}$$

…and this $Al^{3+}$ in solution then reacts with $H_2O$ to form $H^+$ through hydrolysis:

$$Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightleftharpoons Al(OH)_{3(s)} + 3H^+_{(aq)}$$

Once in solution, the $H^+$ can then react with more carbonate from the calcite (see the **acid-base reaction** above). Incidentally, adding liming agents like limestone help add Ca and Mg (Ca from calcite and dolomite found in limestone, and Mg from dolomite only). This is beneficial because, as mentioned earlier, problematic acid soils are commonly deficient in these nutrients.

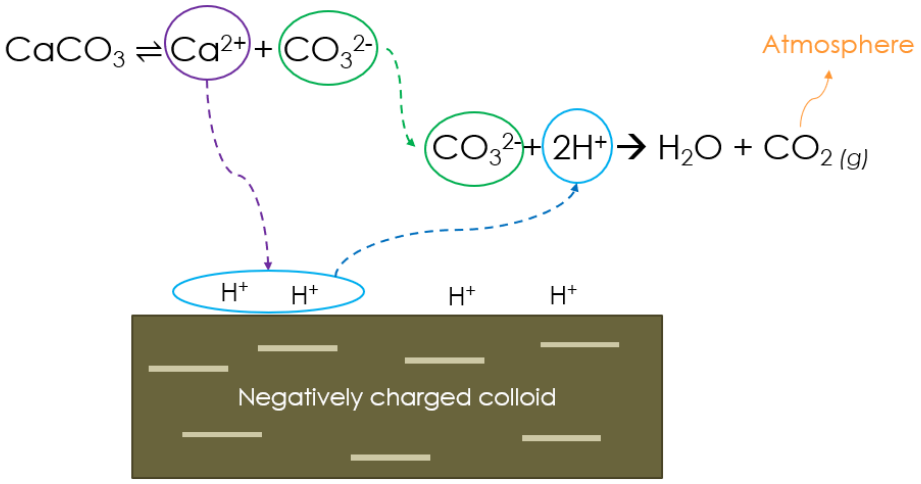



Diagram showing how $Ca^{2+}$ from calcite replace $H^+$ on colloid surfaces, thereby helping the carbonate ($CO_3^{2-}$) from calcite react with the $H^+$.

Thus calcite and other liming agents raise the pH of acid soils by accepting $H^+$ (i.e. acting as bases), and the presence of alkali and/or alkaline earth metals like $Ca^{2+}$ therein both augment their efficiency and provide plant nutrients.

For optimal results, soil in most cases should be limed to pH ~6.5. Doing so requires neutralizing not only the acid cations ($H^+$ and $Al^{3+}$) in solution but also those adsorbed to surfaces (acid cations inside particles do not require neutralization because they affect pH very slowly, over the course of many years). Liming to pH ~6.5 instead of ~7 reduces the risk of overshooting and causing the soil to become alkaline (pH > 7). Check out the next chapter on alkaline soils for more information about how high pH can be bad for plant growth.



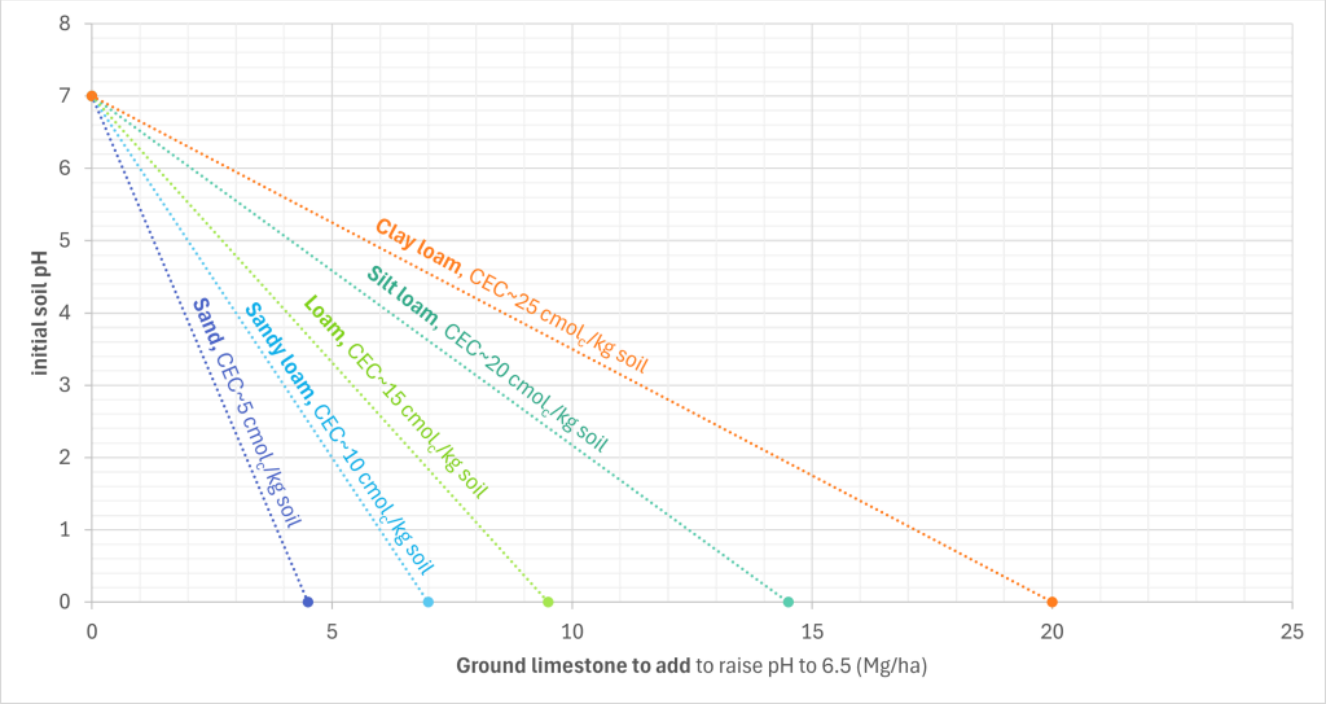
Limestone [Photo Credit: "Limestone" | James St. John | CC BY 2.0]



Liming of a field in Devon, UK [Photo Credit: "Spreading Lime" | Mark Robinson, CC BY 2.0]

## Estimating the Limestone Requirement Using pH and Soil Texture

The amount of agricultural lime needed to raise the pH of a soil is known as the **limestone requirement**, and can be calculated based on its pH and CEC. However, sometimes CEC isn't known. In this case, we can estimate the limestone requirement based on initial soil pH and texture instead using the below graph.

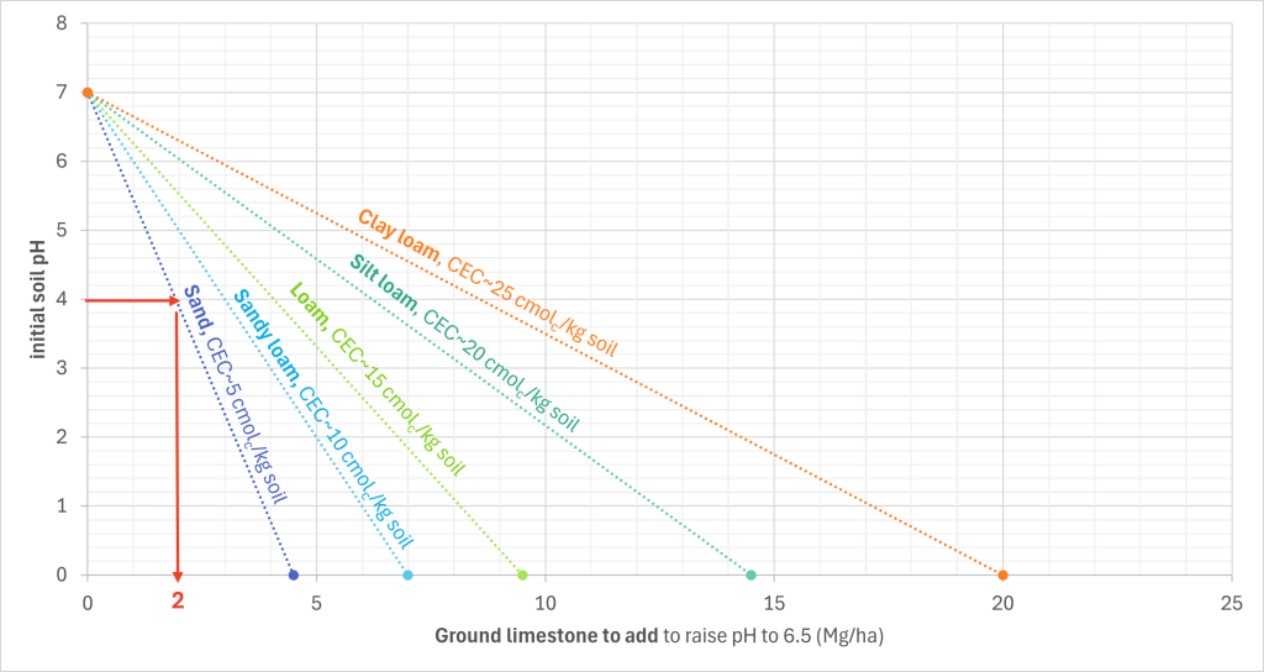



Graph showing the relationship between and ground limestone needed to raise soil pH to 6.5 for five different general soil texture categories. This graph assumes a relatively average soil mineralogy typical of temperate, humid climates common in the northern US and southern Canada. Consequently, using it for soils from the tropics will likely result in inaccuracies because highly weathered colloids found in tropical soils (ex: kaolinite, gibbsite) have lower CECs. If the soil's CEC is known, you can choose the appropriate line in the graph using the CEC instead of the texture. [Adapted from *The Nature and Properties of Soils* by Brady and Weil, 2017]

To use the graph, find the initial soil pH on the y-axis and draw a line to the curve pertaining to your soil's texture. Then, we draw another line straight down, parallel to the y-axis. Then when this vertical line reaches the x-axis, the x-axis value is the limestone requirement.

## Example limestone requirement estimation

When a soil with a **sand** texture has a **pH of 4**, we find 4 on the y-axis, draw a horizontal line to the sand curve, and then draw a vertical line straight down. This intercepts the x-axis at 2, so we know that 2 Mg/ha is the liming requirement.




Example of how to estimate the limestone requirement of a sand soil with an initial pH of 4. Note that "**clay loam**" refers to all clay loams (sandy clay loam, clay loam, and silty clay loam). **Loamy sands**' liming requirements can be calculated by averaging sand and sandy loam. The amount of limestone needed for **clays** is not shown because it depends on the clay minerology and CEC, so the clay minerals and/or CEC of the clays need to be determined first before calculating the liming requirement of clays. See the cation saturation percentages chapter for more information. [Adapted from *The Nature and Properties of Soils* by Brady and Weil, 2017]

## Using Acid Saturation to Calculate Liming Requirements

Beyond estimation, how can you calculate liming requirements more precisely?

To lime an acid soil, you must neutralize both the acid cations in solution (called *active acidity*) exchangeable acid cations adsorbed to surfaces (called *exchangeable acidity*). In an acidic soil, the amount of exchangeable acid cations (mainly adsorbed to colloids) far outweighs the amount of acid cations in solution. Therefore, if we know the CEC and the acid saturation (AS) of a soil, we can estimate the liming requirement following the steps below.

1. First, calculate the *exchangeable acidity* by multiplying the acid saturation (as a fraction) by the cation exchange capacity:

$$EA = AS*CEC$$

2. Then, calculate the mass of the soil:

$$M_s = D_b*V_s$$

3. Next, multiply the mass of the soil by the exchangeable acidity in cmolc/kg to get the total exchangeable acid cations in $cmol_c$:

$$TEA = EA*M_s$$

4. Then, convert the units to kg of $CaCO_3$ to get the calcite requirement (CR):

$$CR = TEA*(100\ g\ CaCO_3/mol)$$

5. Finally, most agricultural liming products do not have 100% effectiveness, or **effective calcium carbonate equivalent** (ECCE). ECCE measures how much acid agricultural liming products can neutralize *relative to pure, powdered calcite.* The higher ECCE, the more effective the liming agent is, and the less needs to be applied; the lower the ECCE, the less effective the liming agent is, and the more needs to be applied. So, when ECCE < 100% (as is almost always the case), we have to calculate the liming requirement (LR), by dividing the calcite requirement (CR) by the ECCE:

$$LR = CR \div ECCE$$

This calculation assumes that the amount of acid cations in solution is negligible compared with the

amount on exchange sites. Refer to the examples below for how to adjust the steps based on the volume of soil, provided units, and desired output units.

## Example Calculation 1: Liming a raised bed

For a raised bed 1 $m^3$ in volume, containing a soil with bulk density of 1.3 $g/cm^3$, a CEC of 20 $cmol_c/kg$, and an acid saturation of 60%, how much agricultural lime is needed? Assume the agricultural lime (ground up limestone) has an ECCE of 80% (i.e. 80% of the limestone is calcite that will dissolve in the near term).

1. First, calculate the *exchangeable acidity* by multiplying the acid saturation (as a fraction) by the cation exchange capacity:

$$EA = AS*CEC$$

$$= (20\ cmolc/kg * 0.6\ cmol_c\ of\ acid\ cations/total\ cmol_c)$$

$$= 12\ cmol_c\ acid\ cations/kg$$

2. Then, calculate the mass of the soil (notice the conversion factors used to convert g to kg and $m^3$ to $cm^3$)::

$$M_s = D_b*V_s$$

$$=(1.3\ g/cm^3 \div 1000\ g/kg)*(1\ m^3 * 100^3\ cm^3/m^3)$$

$$=1300\ kg$$

3. Next, multiply the mass of the soil by the exchangeable acidity in cmolc/kg to get the total exchangeable acid cations in $cmol_c$:

$$TEA = EA*M_s$$

$$= 12\ cmol_c\ acid\ cations/kg * 1300\ kg$$

$$= 15600\ cmol_c\ acid\ cations$$

4. Then, convert the units to kg of $CaCO_3$ to get the calcite requirement (CR):

$$CR = TEA*(0.0005\ kg\ CaCO_3/cmol_c)$$

$$= 15600\ cmol_c*(0.0005\ kg\ CaCO_3/cmol_c)$$

$$=7.8\ kg$$

5. Finally, calculate the liming requirement (LR), by dividing the calcite requirement (CR) by the ECCE. The ECCE needs to be written as a fraction, 80% becomes 0.8:

$$LR = CR \div ECCE$$
$$=7.8\ kg \div 0.8$$
$$= \mathbf{9.75\ kg}$$

Notice how more lime is needed when the liming agent is just 80% effective. If it were 100% effective, we could have just added 7.8 kg of agricultural lime – but because it was just 80% effective, we have to add 9.75 kg.

## Example Calculation 2: Liming one acre-foot of soil

Now, imagine you need to neutralize the acidity of a whole acre of soil, 1 foot deep. If soil still has a bulk density of 1.2 g/cm$^3$, a CEC of 15 cmol$_c$/kg, and an acid saturation of 70%, how much agricultural lime is needed? Assume the agricultural lime (ground up limestone) has an ECCE of 90% (i.e. 90% of the limestone is calcite that will dissolve in the near term).

1. First, calculate the *exchangeable acidity* by multiplying the acid saturation (as a fraction) by the cation exchange capacity:

$$EA = AS*CEC$$
$$= (15\ cmolc/kg * 0.7\ cmol_c\ of\ acid\ cations/total\ cmol_c\ )$$
$$= 10.5\ cmol_c\ acid\ cations/kg$$

2. Then, calculate the mass of the soil. One acre-foot is equal to 1233 cubic meters, so:

$$M_s = D_b*V_s$$
$$=(1.2\ g/cm^3\ \div 1000\ g/kg)*(1233\ m^3 * 100^3\ cm^3/m^3)$$
$$=1479600\ kg$$

3. Next, multiply the mass of the soil by the exchangeable acidity in cmolc/kg to get the total exchangeable acid cations in $cmol_c$:

$$TEA = EA * M_s$$
$$= 10.5\ cmol_c\ acid\ cations/kg * 1{,}479{,}600\ kg$$
$$= 15{,}535{,}800\ cmol_c\ acid\ cations$$

4. Then, convert the units to kg of $CaCO_3$ to get the calcite requirement (CR):

$$CR = TEA * (0.0005\ kg\ CaCO_3/cmol_c)$$
$$= 15{,}535{,}800\ cmol_c * (0.0005\ kg\ CaCO_3/cmol_c)$$
$$= 7{,}768\ kg$$

5. Finally, calculate the liming requirement (LR), by dividing the calcite requirement (CR) by the ECCE. The ECCE needs to be written as a fraction, 90% becomes 0.9:

$$LR = CR \div ECCE$$
$$= 7{,}768\ kg \div 0.9$$
$$= \mathbf{8{,}631\ kg}$$

Optionally, if metric tons are preferred, we can divide by 1000 to get metric tons (denoted as Megagrams, Mg):

$$8{,}631kg \div 1000\ kg/Mg$$
$$\mathbf{= 8.631\ Mg}$$

If short tons are desired instead, we can divide kilograms by 907.2 kg/ton:

$$8{,}631kg \div 907.2\ kg/ton$$
$$\mathbf{= 9.51\ tons}$$

The calculated amount, no matter whether it's in metric tons or short tons, is the amount needed to neutralized the exchangeable acidity only in the top 1 ft only of soil, spread over 1 acre. We're assuming here that:

- the movement of acid cations upwards from below the 1 ft depth will be negligible over the course of the growing season
- the amount of acid cations in solution is negligible compared with the amount on exchange sites

You can find three methods for determining liming requirements, including one nearly identical to this

one, in the Soil & Plant Growth Laboratory Manual – Exercise 6A. Note that some definitions of ECCE differ from what's used here. In this chapter, ECCE is a percent or fraction, but other definitions use absolute units instead.

## Benefits of Liming Acid Soils

From the soil acidity impacts outlined in the acid soils chapter, we can infer that raising problematic acid soil pH to ~6-6.5 would normally result in:

- Reduced aluminum toxicity due to decreased solubility of $Al^{3+}$
- Reduced risk of transition metal micronutrient toxicity ($Fe^{2+}$, $Mn^{2+}$, $Cu^{2+}$ and $Zn^{2+}$)
- Increased cationic macronutrients: $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$, because:
  - Calcite directly adds $Ca^{2+}$, and dolomite adds both $Ca^{2+}$ & $Mg^{2+}$
  - Increasing pH increases CEC, enhancing cation retention
- Increased plant-available P due to less with Al and Fe precipitating with $PO_4^{3-}$
- Increased activity of potentially beneficial microbes, as well as earthworms

Remember to avoid overshooting – these benefits will be overshadowed by alkaline soil problems if a pH of 7 is exceeded. That is why we aim for a pH of 6 to 6.5.

## Key Takeaways

- Soil acidity can be alleviated by adding **liming agents** to raise the pH. The most common is agricultural lime.
    - **Agricultural lime** = ground-up limestone, containing the alkaline, carbonate minerals **calcite** ($CaCO_3$) and/or **dolomite** ($(Ca,Mg)CO_3$)
    - Target a pH of ~6.5 for optimal results
- The liming requirement can be *estimated* from soil texture and pH using a graph
    - The graph provided here is only for humid, temperate regions.
    - For other regions, you must first determine the CEC to use the graph (or the calculation below).
- The liming requirement can be calculated from the acid saturation (%AS), CEC, volume ($V_s$), and bulk density ($D_b$) of the soil using these equations:

$$EA = AS*CEC$$

$$M_s = D_b*V_s$$

$$TEA = EA*M_s$$

$$CR = TEA*(100\ g\ CaCO_3/mol)$$

$$LR = CR \div ECCE$$

CHAPTER 36

# Salt-affected Soils: Salinity and Sodicity

**Rivka Fidel**

## Learning Objectives

- Define: **salinity, sodicity, saline soil, sodic soil, saline-sodic soil, EC, ESP, SAR**
- Calculate: **ESP**
- Explain what type of climates would you expect to find acid, alkaline and salt-affected soils in and why
- Describe why plants have trouble growing in saline, saline-sodic, and sodic soils
- Compare and contrast approaches for reclaiming saline, saline-sodic, and sodic soils

**Keywords**: saline, saline-sodic, sodic, reclaiming soils

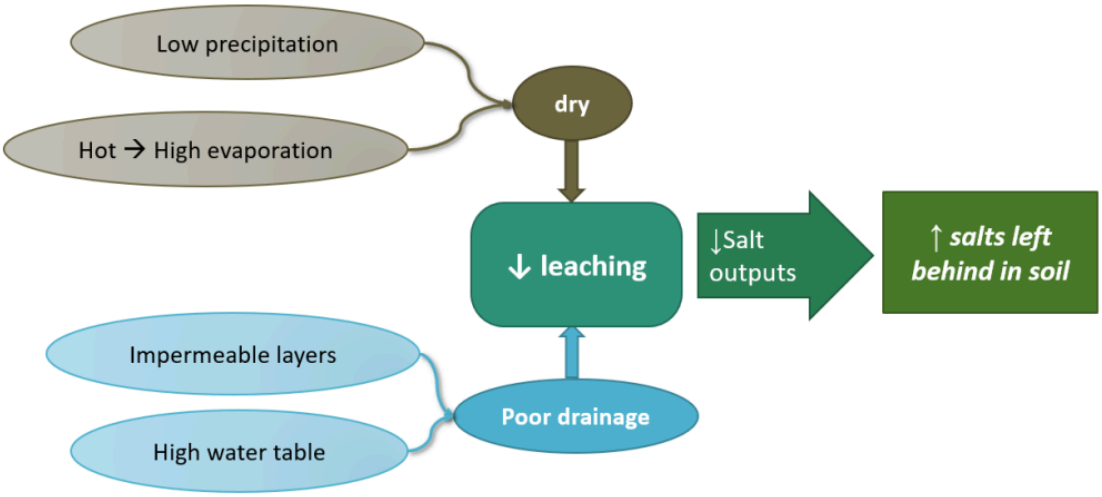
## Salt-affected soils

**Salts** are defined as ionic compounds containing a cation and an anion. The types of salts accumulating in salt-affected soils specifically tend to contain an alkali metal or alkaline earth metal cation bonded to a nonmetal anion. In order to translocate downwards through the soil, the salts need to be fairly soluble so that they can first dissolve in the topsoil, then move down and precipitate in the subsoil. Here are some example salt dissolution reactions for common salts found in soil:

- Calcium carbonate: $CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}$
- Sodium chloride (table salt): $NaCl \rightleftharpoons Na^{+} + Cl^{-}$
- Gypsum: $CaSO_4 \cdot 2H_2O \rightleftharpoons Ca^{2+} + SO_4^{2-} + H_2O$
- Potassium nitrate (fertilizer): $KNO_3 \rightleftharpoons K^{+} + NO_3^{-}$

**Salt-affected soils** are soils with excessive total salt concentrations or imbalances among salts such that they inhibit plant growth. These soils are most commonly found in semi-arid to arid regions, because in dry climates the low precipitation leads to low leaching of salts, and instead salts accumulate in the soil profile. Salt accumulations are therefore common among Aridisols, especially in B horizons. Salt-affected soils can also be found in areas with poor drainage such as closed basins. *Closed basins* are areas with a bowl-like shape where the water cannot flow out to a nearby stream, but instead collects in the middle where much of it evaporates, leaving behind salts. Such areas generally also have high clay content and poor drainage due to the downhill movement of clays, preventing salts from leaching out to the groundwater table and further promoting salt accumulation.

In the environment where a soil is developing, salts originate from weathering of minerals. From there they dissolve, and move with the flow of water through soil, groundwater, and/or streams. Ultimately these salts end up in the ocean. If groundwater or stream water are used for irrigation, this adds salt back into the soil; and if much of this evaporates due to hot, dry conditions, salts can accumulate in irrigated soils. Such salts in irrigation water pose common challenge farmers in arid regions have faced for millennia, from Mesopotamia to the modern Western US and Middle East. Furthermore, coastal regions face a threat of incoming salts from ocean water, in the form of salty sea spray, saltwater intrusion into fresh groundwater, and, in more recent decades, sea level rise. Such ocean-derived salts can quickly turn healthy coastal soils into salt-affected soils.




Conceptual diagram showing how both dry conditions and poor drainage together contribute to the accumulation of salts in soil. (This includes alkaline salts like $CaCO_3$ that raise the pH, see the Alkaline Soils chapter). [Image Credit: Rivka Fidel]

## Example Salt-Affected Soil

An example of an extremely salt-affected soil is found at Willcox Playa, in Cochise County, Arizona. Willcox Playa is located in a closed basin, meaning it's a the lowest point of a bowl-like area surrounded by hills and mountains. As such the water from the rest of the landscape flows towards the playa, with no other outlet. Thousands of years ago – in the late Pleistocene Epoch, when the local climate was wetter – the inflow of water once formed Lake Cochise, and when the climate became drier ~11,000 years ago, the lake water evaporated, leaving behind salts. Over time the water continued to flow towards the playa, carrying with it salts from higher in the landscape, and evaporating – leaving behind even more salts. The subsoil is furthermore very clayey, reducing leaching of salts out of the soil through percolation and drainage. The soil hence grew ever more salty over time, until it could no longer support most plants.




A map of the Willcox Playa drainage basin, with arrows indicating the downhill flow of water towards Willcox Playa itself [Image Credit: Geology of the Willcox Playa, Schreiber 1978, NMGS]



View of the edge of Wilcox Playa, looking outward to the West. Note the white salts on the surface. [Photo Credit: Rivka Fidel]



View looking towards the center of Wilcox Playa. Note the lack of vegetation, especially near the inside of the playa. [Photo Credit: Rivka Fidel]

## Saline and Sodic Soils

There are three types of salt-affected soils: saline, sodic and saline-sodic. These are classified based on their **salinity** (total salt content) and **sodicity** (the proportion of sodium).

## Salinity

### Measuring Salinity

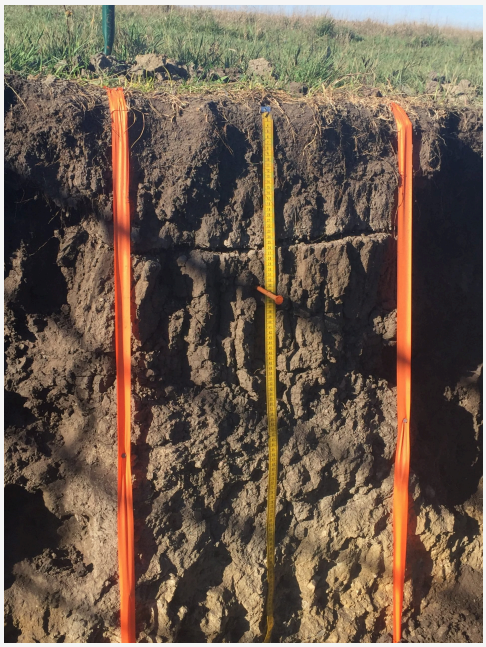
Total salt concentrations can be quickly measured using **electrical conductivity** (EC). Salts generally increase the EC of water because the charges of ions (both cations and anions) in salts help carry electrical current through water, increasing its electrical conductivity. Thus, the higher a soil's EC, the saltier it is, and the greater its **salinity**. *Soils with EC's greater than 4 dS/m are considered* ***saline soils***.

#### Salinity testing via the saturated paste method

Watch this video for more information: https://www.youtube.com/watch?v=FEZGt47p4Cg

## Saline Soils

In saline soils, typical plants may experience osmotic stress. **Osmotic stress** occurs when a high total salt concentration lowers osmotic potential so low that plants have trouble getting water. As you may recall from the soil water chapter, water flows from high to low water potential. Also recall that *as salt concentration increases, osmotic potential decreases*. So, if the soil water potential is too low because the soil is too salty, plants can't get water. In other words, the salts may literally suck water out of the plants! Some plants, called *halophytes*, have evolved to keep their water potentials low enough to grow in saline soils. These plants grow in naturally saline soils found in coastal areas and closed basins. Generally though, typical plants struggle to get water in saline soils.



Saline soil near Redfield, SD. In this soil, the salts are not concentrated enough to be visible. [Photo credit: Amber Anderson]



Salts accumulating on the soil surface in a hoop house. [Photo Credit: Amber Anderson]

### More About Osmotic Stress

Watch this video for more information: Unavailability of water in saline soils

# Sodicity

## Measuring Sodicity

Sodicity is measured using **exchangeable sodium percentage (ESP)**, the fraction of sodium out of the total exchangeable ions:

$$ESP = \frac{exchangeable\ Na^+}{CEC} = \frac{[Na^+]}{[Ca^{2+}] + [Mg^{2+}] + [K^+] + [Na^+]}$$

ESP is calculated from $cmol_c$/kg of Na, and the CEC in $cmol_c$/kg. Here the CEC can be estimated as the sum of all of the base cations, also in $cmol_c$/kg.

Sodicity of soil can alternatively be measured using **Sodium Adsorption Ration (SAR),** which is calculated from concentrations of soluble cations *in a soil extract or in water*, in units of mmol/L:

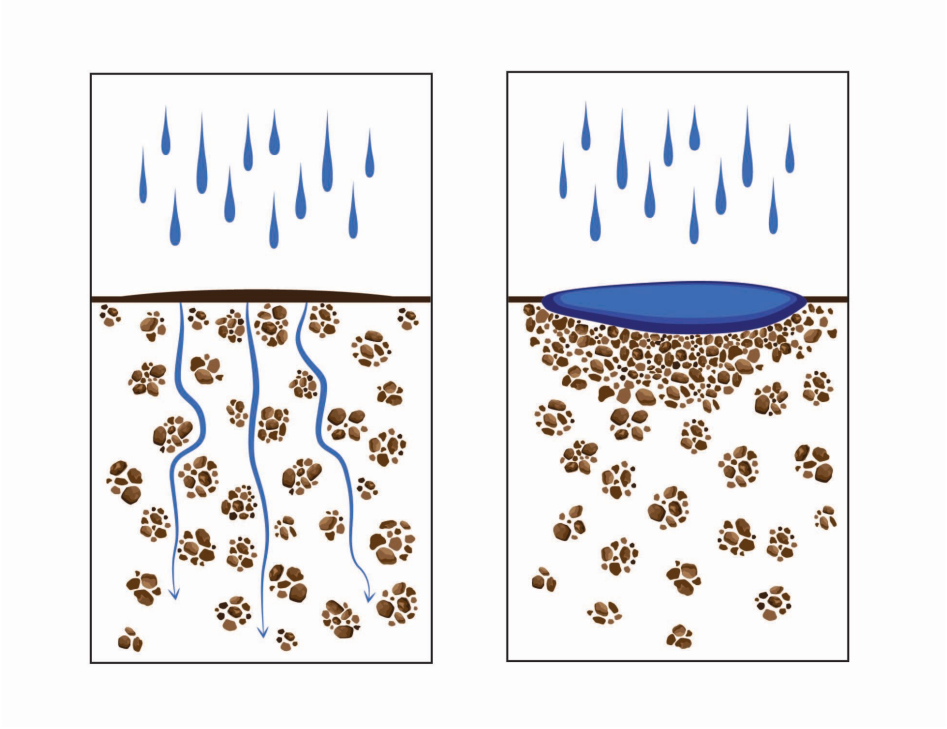
$$SAR = \frac{[Na^+]}{\sqrt{0.5[Ca^{2+}] + 0.5[Mg^{2+}]}}$$

The higher the ESP or SAR of a soil, the greater its **sodicity**. Soils with an ESP > 15% or a SAR > 13 *and* EC < 4 are considered **sodic soils**. That means a soil must have both a high proportion of sodium relative to other nonacid cations *and* low total salts to be sodic.

## Sodic Soils

Compared with the other nonacid cations, $Na^+$ is special in that it both degrades soil structure and increases soil alkalinity. Thus, excess sodicity degrades the soil both chemically and physically.

When present in excessive amounts (>15% on a molar basis), it causes dispersion of clays and a subsequent decline in soil aggregation. **Dispersion** is when clay particles, instead of sticking together, come apart. This is a problem because clays are important for aggregation or “clumping” of soil, which improves soil physical properties such as infiltration, drainage, and aeration. Once dispersed, clays can also flow through the soil and clog up pores, further reducing infiltration and drainage. When clay dispersion occurs on the surface of the soil, creating a sort of clayey mud puddle, the clays harden as they dry, forming a hard crust in a phenomenon called **crusting**. In addition to reducing infiltration, these crusts make it difficult for young plants to break through the soil and reach sunlight.



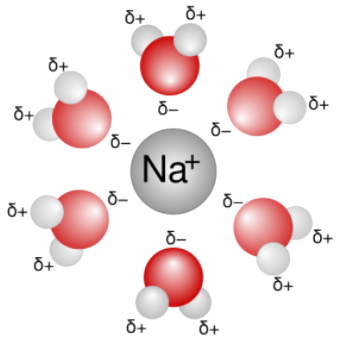
Flocculated soil (left) vs dispersed soil (right). Normal and saline soils tend to be well-flocculated, leading to good aggregation and structure. This creates sufficient macropores for good infiltration and drainage, as shown on the left. Sodic soils, however, tend to be dispersed (poorly flocculated), and consequently have poor aggregation and structure. This results in poor infiltration and drainage, leading to ponding, as shown on the right. [Image Credit: Soil Structure: The Roles of Sodium and Salts by Jim Walworth of Arizona Cooperative Extension; used with permission.]

Then, sodium increases soil pH to above 8.5, which inhibits the growth of average plants. Sodium increases the solubility of carbonates ($CO_3^{2-}$ -bearing compounds), because sodium carbonate ($Na_2CO_3$, also called super washing soda) is much more soluble than the more common calcium carbonate ($CaCO_3$, aka calcite). As a result, soils rich in $Ca^{2+}$ have low $CO_3^{2-}$ solubility, and so $CaCO_3$-rich soils typically have pHs ranging from 7.6-8.4. However, excessive $Na^+$ *relative to other nonacid cations* helps the carbonate ($CO_3^{2-}$) dissolve much better than it would in a soil with sufficient $Ca^{2+}$ or $Mg^{2+}$, raising the pH to 8.5 and above.

## Why do sodic soils undergo dispersion?

The "sod" in **sodic** stands for "sodium." Sodium (Na) is special among the four main nonacid soil cations (Na, K, Mg and Ca) in that it has the largest **hydrated radius** relative to its charge. The hydrated radius is the distance from an ion to the edge of the waters surrounding it.

The large hydrated radius of Na acts like a "bumper" surrounding each sodium ion, preventing it from getting close to negatively charged surfaces like those found on phyllosilicate clays. When many Na ions are present, they create a thick ion swarm that keeps clay particles dispersed. This causes the soil to lose much of its aggregation and structure.




A hydrated sodium ion.

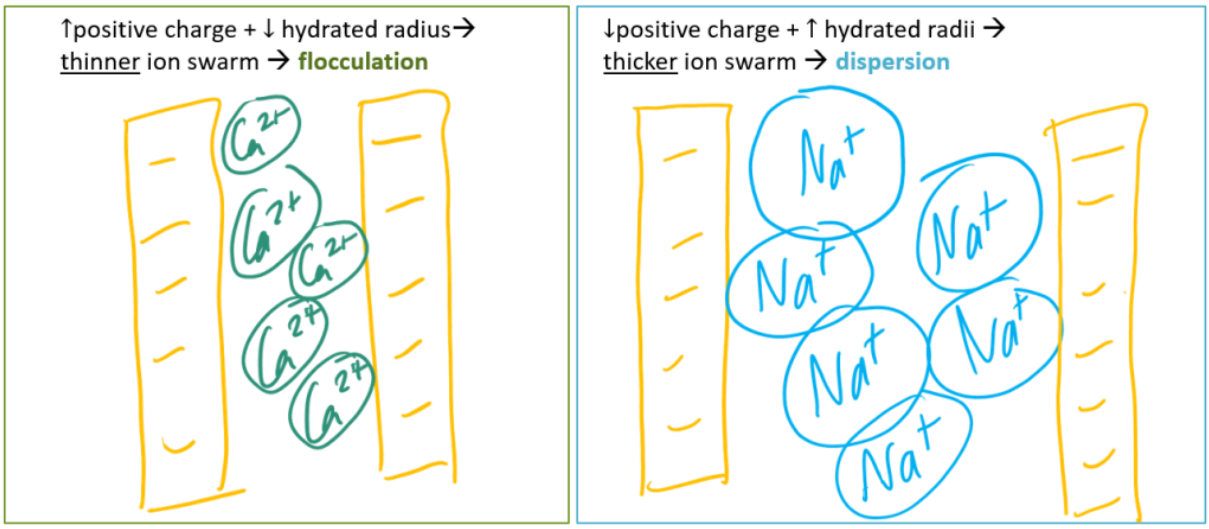
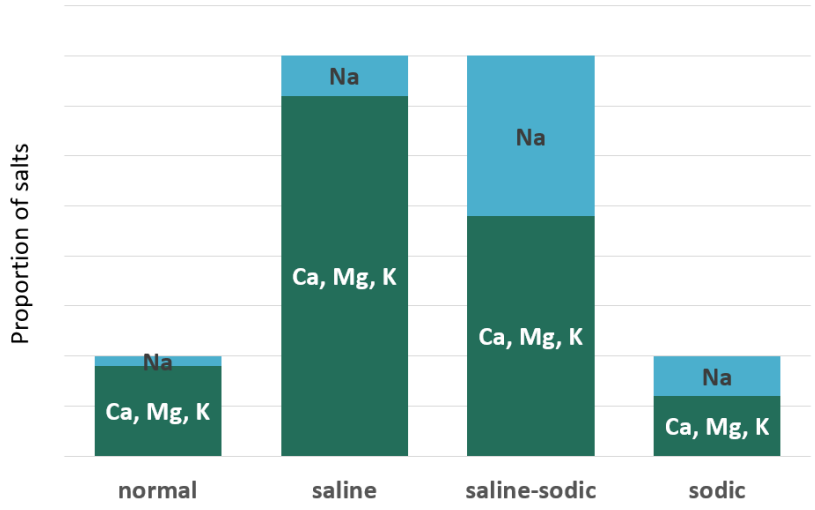



Diagram illustrating the combined effects of charge and hydrated radius on flocculation and dispersion of clays. The clay particles are shown as yellow rectangles with "-" signs representing negative surface charges. The ions have circles around them representing the size of their hydrated radii. Notice how sodium (right) has a larger hydrated radius than calcium (left). [Image credit: Rivka Fidel]

This video shows how dispersion works, though the cation's hydrated radii aren't shown (only charges): Dispersion of clay plates by sodium in soil

## Saline-Sodic Soils

What about soils that have too much total salts *and* too much sodium? These soils, which have ESP > 15% (or SAR > 13) and EC > 4 are called **saline-sodic** soils. Interestingly, these soils in fact have better structure than sodic soils. Why? Because the presence of excess *total* salts (aka salinity) actually negates the effects of excess sodium (aka sodicity). This occurs because as salinity (and EC) increase, flocculation and therefore aggregation increase. As a result, saline-sodic soils are more fertile than sodic soils, but less fertile than saline soils.




Conceptual graph illustrating the difference between normal, saline, saline-sodic, and salt affected soils. Notice the differences in the proportions of sodium ($Na^{+}$) and other nonacid cation salts ($Ca^{2+}$, $Mg^{2+}$ & $K^{+}$). Note that in sodic and saline sodic soils, Na+ constitutes 15% *or more* of the nonacid cation salts; however, in this diagram, arbitrary numbers greater than 15% were chosen.

### More About the Sodium Adsorption Ratio (SAR)

Watch this video for more information: What is the sodium adsorption ratio?

## Remediating Salt-Affected Soils

Many soils are naturally saline and/or sodic, and still support the growth of native salt-adapted plants. In this case, the ecosystem can remain healthy without intervention. However, remediation becomes necessary when a soil has become saline or sodic as a result of poor management, or when a

landowner needs to grow crops on a naturally salt-affected soil. Irrigated farmland in dry regions commonly becomes saline and/or sodic over time due to the presence of salts or predominance of sodium in irrigation water. It is ideal to prevent the development of salinity or sodicity in the first place by using low EC, low SAR irrigation water (i.e. water low in total salts and in sodium).

When soils do need remediation, saline soils need different treatment from sodic soils. **Saline** soils simply require irrigation with excess clean water having a low EC. This washes excess salt from the upper soil layers where plants grow down to the groundwater permeating lower soil layers or fractured rock below.

**Sodic** soils, however, first require application of gypsum ($CaSO_4 \bullet 2H_2O$) *before* adding excess clean irrigation water to remediate them. The purpose of the gypsum is to replace the Na+ adsorbed to soil colloid surfaces with $Ca^{2+}$:

$$Na^+[Colloid]\ Na^+ + CaSO_{4(aq)} \rightleftharpoons Ca^{2+}\ [Colloid] + Na_2SO_{4\ (aq)}$$

…where [Colloid] stands for any negatively charged colloid particle. Note that *calcite ($CaCO_3$) should never be added to sodic soils*. This is because unlike gypsum, calcite contains $CO_3^{2-}$; this base would further increase the pH of sodic soils, which are already too alkaline. The $SO_4^{2-}$ in gypsum, on the other hand, does not increase the pH because, as the conjugate anion of a strong acid, it cannot accept $H^+$ in soil.

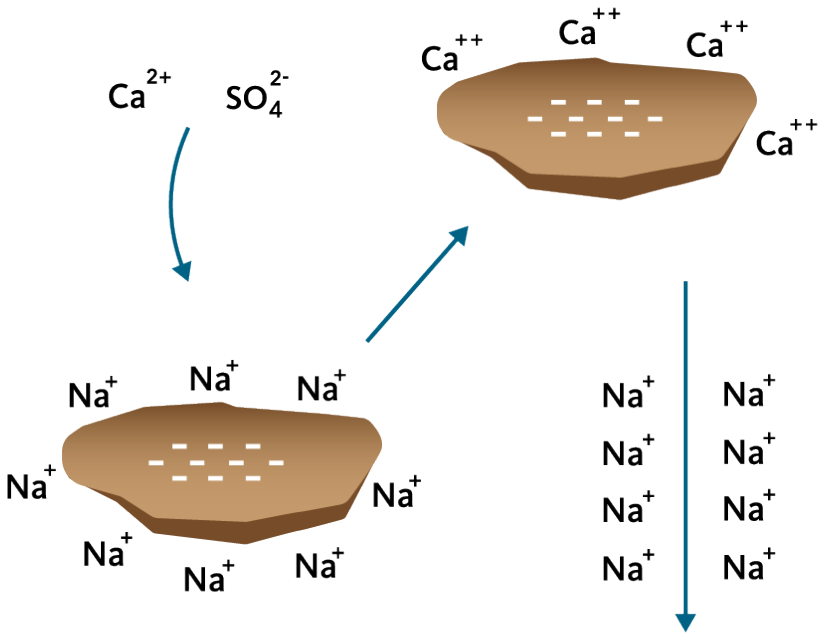
In addition to $Ca^{2+}$, $H^+$ can be used to remediate sodic soils. H+ can be added in the form of sulfuric acid ($H_2SO_4$), which is a strong acid that completely dissociates into $2H^+$ and $SO_4^{2-}$ in water (technically $HSO_4^-$ is not a strong acid, but it's strong enough that it will completely dissociate at typical soil pH's ranging from 4 to 10). The $H^+$ both lowers the pH and replaces $Na^+$ adsorbed to colloids.

This reaction shows how $H^+$ replaces adsorbed $Na^+$:

$$Na^+_2[Colloid] + H_2SO_{4(aq)} \rightleftharpoons H_2{}^+[Colloid] + Na_2SO_{4\ (aq)}$$

…and this reaction shows how $H^+$ neutralizes carbonates:

$$H_2SO_{4(aq)} + Na_2CO_{3(aq)} \rightleftharpoons CO_{2(g)} + Na_2SO_{4(aq)} + H_2O$$




When gypsum is added to sodic or saline-sodic soil, the $Ca^{2+}$ replaces exchangeable sodium, forcing the $Na^{+}$ ions into solution. Then, adding water helps the $Na^{+}$ ions leach out of the soil. Sulfate ($SO_4^{2-}$) is merely a spectator ion in this process. See the below videos for demonstrations of this effect. [Image Credit: Soil Structure: The Roles of Sodium and Salts by Jim Walworth of Arizona Cooperative Extension; used with permission.]

### Videos Showing the Effect of Gypsum on Sodic and Saline-Sodic Soils

Watch this video for more information: Visualizing soil properties: Dispersion and flocculation

For more information about how to manage salt-affected soils, see Managing Salt-Affected Soils for Crop Production.

## Summary Table for Acidity, Alkalinity, Salinity and Sodicity

This table summarizes the properties and remediation techniques for "problem soils" we've explored in the last few chapters.

| | Acid soil | Alkaline soil | Saline soil | Saline-Sodic soil | Sodic soil |
|---|---|---|---|---|---|
| **Defining feature** (what are they?) | Lots of $H^+$ | Lots of $OH^-$ | Too much total salt | Too much total salt and Na | Too much Na relative to other salts |
| **Identified by** | pH < 7<br>*(only a problem if pH <5.5)* | pH > 7<br>*(bigger problem if pH > 8.5)* | EC > 4<br>ESP < 15%<br>SAR < 13<br>pH 7-8.5 | EC > 4<br>ESP >15%<br>SAR > 13<br>pH > 7 | EC < 4<br>ESP > 15%<br>SAR > 13<br>pH > 8.5 |
| **Soil structure** | Good | Good | Good | Adequate to good | Poor |
| **Environmental conditions** (where are they?) | Heavy leaching conditions (Spodosols, Ultisols + Oxisols) | Dry, arid regions<br>Limited leaching conditions | | | |
| **Remediation** (how do we fix them?) | Liming (add calcite, i.e. $CaCO_3$) | Usually too expensive to add enough acid | Add water *(low EC, low SAR)* | Gypsum ($CaSO_4$), then water *(low SAR water is best)* | |

Note: A soil suitable for growing average crops (not in the table) would have a pH between 6-7, EC < 4 dS/m, and ESP < 15%.

## Key Takeaways

Salt-affected soils form in dry conditions. There are 3 types:

- **Saline** soils
  - Too much total salt
  - EC > 4 dS/m & ESP < 5%
  - Cause osmotic stress
  - Good structure, infiltration, and drainage
  - To remediate: add high quality (low-salt, low-sodium) water
- **Sodic** soils
  - Too much sodium *relative to other exchangeable cations*
  - EC < 4 dS/m & ESP > 15%
  - pH > 8.5
  - Poor structure, infiltration and drainage
  - To remediate: add gypsum, then water low in salts/sodium
- **Saline-sodic** soils
  - High total salts *and* sodium relative to other exchangeable cations
  - EC > 4 dS/m & ESP > 15%
  - Adequate to good structure, infiltration, and drainage
  - To remediate: add gypsum, then high-quality water low in salts/sodium

PART VII

# Soil Management

CHAPTER 37

# Soil Testing

**Amber Anderson**

## Learning Objectives

- Outline steps for taking a reliable soil sample
- Match soil test output levels to recommended management
- Predict expected relative test values given site characteristics

**Keywords**: soil testing, soil sampling, analyzing soil sample results

Farmers utilize soil sampling to determine soil fertility, pH, nutrient variability, organic matter, and texture. Soil testing might be recommended for several reasons, including unexplained nutrient deficiencies. When compared to a tissue or sap test, soil sampling is typically a less expensive option but may not be the most appropriate for all situations. The test results are meant to guide your management plan for the current or following year. Several factors should be considered when determining when and where to sample.

## When to Soil Sample

- At a time when application can occur before next cropping season or harvest. Typically late summer or early fall in Midwestern US annual systems.
- Consistent time of year each time you soil sample. Commonly every 3 to 4 years following the same crop in the same environmental conditions.

## Places to Avoid when Sampling

- Field edges
- Areas near roads
- Near livestock
- Near buildings or former buildings
- Uneven areas or unusual areas, unless they are given their own sample

## Factors to Remember during Sampling

- History, different past land use can result in different test levels. Sampling the area so one sample does not represent both areas will result in more accurate results.
- Consistent depth, timing, and lab procedures with clean equipment to maintain uniformity and accurate lab results.
- More samples will likely eliminate potential inconsistencies and bias.
- Avoid sampling in poor conditions, like excessively wet or frozen soil conditions.
- Samples should represent a small enough area to be representative, typically no more than 10 acres in annual row crop systems or an acre in more intensively managed situations.

## Best Practices for Sampling

Follow the specific recommendations of your testing laboratory, but generally:

- Use clean equipment
- Subsamples should be used, mixed, and submitted sample used
- Sampling depth as indicated by your test/laboratory
- Differing areas should have their own soil sample, as combining them will not provide reliable results for either area

## Strategies Used for Sampling

### Grid

This method takes samples within regular divisions or zones of equal size, 1, 2.5, 5, or 10 acres. This regular sampling is meant to capture viability across the landscape. The method may be more helpful if the management history is unknown or variable rate application technology will be used. Drawbacks could include the additional cost resulting from more samples and samples less representative of the larger area.

## Zone

This method is used when there is some historical knowledge of the area and to assess changes over time. Areas of similar soils, topography, and management are grouped for testing – samples are taken within the "zones". This method can provide some basic information for management decisions at a decreased cost when compared to grid sampling, but may be less reliable if there is a history of manure application or specific concerns across the field.

# Assessing your Soil Sample Results

Reports received from testing laboratories generally include both a value and a rating, like 'high' or 'very low' to indicate relative status. Fertilizer application, when a soil test level is very high or high, is unlikely to provide economical return on investment and may be environmentally irresponsible. Fertilizer applications with low or very low values are likely to result in yield increases and should generally be applied at rates higher than anticipated crop removal rates.

## Considerations

High pH values may be associated with roads in some areas due to limestone used in road material or the potential transport of liming materials.

Many standard soil tests don't include heavy metals or other potentially harmful contaminants. A test may be warranted if you are producing food in an area with potential contamination (particularly urban areas or former industrial sites).

Previous livestock on the land can contribute to high or very high phosphorus levels long after animals are present. Erosion and/or further application in these areas can negatively impact water quality.

### Soil testing publications

- Taking a good soil sample
- Interpreting results
- Recommendations for Iowa/Midwest US

## Key Takeaways

- Soil testing can be an affordable alternative to a tissue of sap test, though it isn't recommended for all cases.
- Soil sampling should be conducted at a consistent time of year, every 3 to 4 years, in similar conditions.
- To get useful results from soil sampling, do not combine samples from differing areas. Instead gather soils across a grid or from areas with similar soils and management.
- Keep in mind that soil sample results can be affected by the presence of livestock or roads containing limestone.

CHAPTER 38

# Fertilizer Analysis

**Amber Anderson and Arturo Flores**

## Learning Objectives

- Identify components of fertilizers
- Calculate quantity of a given fertilizer needed to meet nutrient needs

**Keywords**: fertilizers, fertilizer components

## Guaranteed Analysis

Commercial fertilizers sold in the US are required to share amount of nutrients contained in the product on the label. The standard way to share this information is called a guaranteed analysis, like 10-10-10. The first number refers to percent nitrogen by weight, the second phosphorus as $P_2O_5$, and the third refers to potassium as $K_2O$. Note that this exact form of nutrient isn't required to be in the bag, but an equivalent amount of P or K is required, so this is simply a standardized way to express quantity of a nutrient.

## Other Material in a Bag

Note that the percentages of N, $P_2O_5$, and $K_2O$ don't add up to 100% of the bag contents. Other materials that wouldn't be counted in this guaranteed analysis number could be nutrient carriers that contain the nutrient, conditioners that improve some property of the material, or inert materials that may make a small quantity of nutrient easier to spread uniformly over a large area.

## Carriers

Not all molecules in a compound are the target nutrient for fertility. In urea, a nitrogen fertilizer, nitrogen is contained, but not all of the molecule.

## Other nutrients

Nutrients besides nitrogen, phosphorus, or potassium are still needed by plants, and may be included in a fertilizer mix. Those contents would not be reflected in the guaranteed analysis of the material

## Conditioners

Some fertilizers have less than ideal handling or storage properties-so materials to prevent caking, adjust the pH, or otherwise create more favorable conditions for storage or handling may be included.

### Example



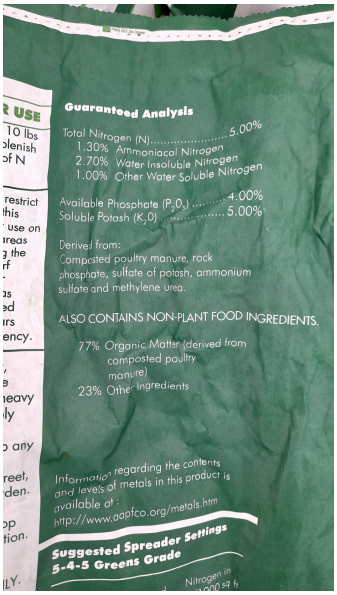

Fertilizer bag from a Costa Rican Coffee Cooperative.

This Costa Rican fertilizer bag has percentages of each nutrient contained instead of the guaranteed analysis required on US fertilizer bags. Note that this label shares nitrogen, phosphorus, potassium, magnesium, calcium, iron, and organic material percentages.

## Example

Organic-derived fertilizer used for turfgrass management:

- Compared to commercial syntethic formulas, this product contains significantly lower levels of each nutrient. The reason is they are meant for soil-nutrient maintenance and not for building the main nutrient pool.
- Also important to note, here, Nitrogen is divided into three categories:
    - **Ammoniacal Nitrogen:** represents instant availability for root absorption.
    - **Water Insoluble Nitrogen:** this is some type of slow-release fertilizer, which means it requires a different process to break down and takes longer to be readily available, reducing leaching potential and providing long-term nutrition.
    - **Other Water-Soluble Nitrogen:** also instant available nitrogen but in a different form than ammoniacal nitrogen.




Organic fertilizer bag for turfgrass. Photo Credit: Arturo Flores.

## Key Takeaways

- Guaranteed analysis on fertilizer bags indicates percentage of N-$P_2O_5$-$K_2O$ contained
- Other materials, like conditioners, carriers, or micronutrients may also be found

CHAPTER 39

# Problem Solving

**Amber Anderson**

## Learning Objectives

- Outline a process to determine potential diagnoses in a problem solving scenario
- Utilize knowledge of soils, nutrient behavior, and other factors to narrow down potential causes
- Determine how you might confirm or rule out potential causes of identified problem

**Keywords**: questions to ask, identifying issues

How might you go about determining or ruling out soil-related causes for a symptomatic plant? Start by asking these questions:

## What is the plant supposed to look like at this stage?

Is it stunted or abnormally colored? Purple leaves in some varieties, particularly horticultural crops, may be normal. However, purple colors in a plant that is not supposed to have that coloration may indicate a phosphorus deficiency.

## Pattern

Is there a pattern in where symptomatic plants are occurring in the field (low spots, edge of field, steep areas)? Area with recent construction or newly replaced topsoil? How about within the plant (new growth vs old growth)?

## Conditions

What have conditions been like in the area recently? Have they been abnormally cold, wet, hot, dry? How about last season (potential herbicide carryover if dry)? Cool springs may contribute to more nutrient deficiency symptoms, as root growth and microbial activity may both be slower than normal.

## Field operations

What has happened to the site recently? Any major disturbance (topsoil removal, compaction, installation that displaced or inverted significant soil)? Application of nutrients or chemical materials?

## Testing

Has any testing been done that may help support a potential nutrient deficiency diagnosis? Soil pH is one that may be helpful if only limited testing has been done, as high pH soils may cause nutrient availability issues with metals like iron. At low pH values, there may be different nutrient deficiencies, or even toxicity of something like aluminum in highly weathered conditions.

## Now what?

In order to support your diagnosis, you may want to gather additional evidence. For example, a soil test if you suspect a nutrient deficiency. Some issues may not have a feasible treatment at the point of diagnosis, like an herbicide carryover due to a dry year, but could be considered in future management of the area if another dry year is expected.

In annual crop management, seeing significant deficiency symptoms throughout the season mean that decreased yield is already expected and it may be too late to adjust conditions for the current crop, so adjustments or applications would likely be for the next season or crop. In perennial crops, other strategies might be more desirable, like foliar application, injections, or more intensive methods. Additionally, considering the soil and potential problems before they are planted means that some issues, like iron deficiency of a full-sized pin oak due to high pH soils, could be avoided. As in many things-an ounce of prevention is worth a pound of the cure.

## Key Takeaways

- Identifying patterns (across the field or within the plant) is important for determining potential causes of the issue:
    - straight lines are likely human-caused,
    - eroded soil areas may show an issue correlated with low organic matter or high pH

CHAPTER 40

# Soil Input Recommendations

**Arturo Flores**

## Learning Objectives

- Interpret soil test reports
- Calculate the required fertilizer to amend soil nutrient deficiencies
- Design fertilizer formulas based on the soil needs and materials available

**Keywords**: soil testing, soil nutrients, fertilizer

## Make soil input recommendations

One of the big questions in agriculture has been and will be 'what and how much should I apply to increase yield?' It is a common question asked by most farmers, with the belief that there is a magic formula to once and for all improve the soil quality and boost yield. However, this is far from being true. As has been discussed throughout this course, soil is a complex and dynamic system. Therefore, improving soil is a holistic process that should consider each one of its factors that could be limiting production. Soil laboratory analysis is an accepted measure performed by farmers around the globe to obtain some insight about what is going on in their soils and use it as a starting point to take management decisions.

The soil test report obtained after analysis may include recommended fertilizer application rates and even recommended products. Nevertheless, this service is not always available or economically accessible for every user. The process of interpreting a soil test report is not rocket science, and with a basic understanding of the overall condition of soil, it is possible for any user to improve the soil quality. It should be noted that a soil test report is not completely accurate and may just represent the condition of the soil where the sample was taken. However, is still valuable to be able to read,

understand, interpret and act according to what the report is telling the user. The most important thing to remember when interpreting soil test results, is that soil quality or fertility is not just a matter of nutrient balance, but also about the chemical and physical conditions of soil, including acidity, salinity, and moisture content.

## FIRST: Evaluate and improve the physical condition of the soil

Porosity and moisture content are limiting factors that can reduce agricultural productivity. Fine soil textures are good for retaining moisture, but bad for resisting compaction. Conversely, sand and gravel retain low quantities of humidity, but resist compaction better than clays. Compacted soils and not granular structures make root growth, water infiltration and percolation significantly harder. When roots can't penetrate deep and water sits for too long on the root-zone (0 – 12 in), the root system becomes shallow and relies on the surface conditions to thrive. This is a problem, especially when water has trouble draining away because waterlogging near the surface increases nutrient reduction reactions and changes the chemical soil conditions. As a result, crops are more susceptible to drought and nutrient deficiencies.

Moreover, soil physical conditions can be managed temporarily to better adequate the soil with optimal growing conditions. Artificial drainage, such as tile pipe or canals can be implemented to reduce waterlogging and increase draining rates. Canals are built to collect excess water from run-off after high precipitation events, and also to regulate the water table, preventing it from reaching the root-zone. Conversely, when soil is too dry, there is no moisture that can be used to absorb nutrients. Nutrients use water as transport to move through the soil and to be absorbed by the plant's roots. Irrigation can be useful to maintain optimal soil moisture and the effects of drought stress, including plasmolysis and the inability to feed on plant nutrients. Surface structure and compaction are modified with soil tilling with chisel and disc plows, or with rotovators. These technologies increase soil porosity in the short term but may lead to the development of hardpans when mechanization occurs regularly on not optimal conditions (eg., excess soil moisture). Soil texture is hardly altered because it requires large amounts of material. This is seen more often in sport turf management, where the soil is amended with large quantities of sand that increase drainage and reduce the risk of compaction. However, the economic cost represents a significant restriction for conventional agriculture, and the incorporation of organic matter is more common for enhancing texture and structure.

Commonly, these problems are not presented in a conventional soil fertility test, unless otherwise specified. However, they can be the reason for crops not being able to thrive as expected. When the growing medium lacks proper soil physical fertility, the application of other inputs, such as lime or fertilizers, may not result in a significant improvement of yield. If the soil's physical condition is considered optimal, it is time to address the chemical fertility problems identified from the soil test report.

## SECOND: Improving Soil Chemical Fertility

Soil pH is the primary chemical property regulating nutrient availability, and most soil test reports include this value. Acid soils (pH<7) tend to have more aluminum readily available, which results toxic for plants, and calcium, phosphorus and magnesium are less available. Alkaline conditions (pH>7) decrease phosphorus and micronutrients availability and increase salinity susceptibility. Nutrient deficiencies caused by soil pH can be reduced with the application of lime (increase pH), or with acidifying materials containing sulfur (reduce pH). These solve the problem in the short term and pH will return to the original level if it is not constantly managed. Liming corrects passive acidity but does not change soil natural behavior and mineralogy, which is the reason for the soil's natural pH. For example, in tropical countries like Costa Rica where precipitation rates are very high (>120 in/year), it is common to find soils with pH of 5 or even lower. Thus, for farmers in the region, liming pastures and other agricultural fields becomes a regular practice every one or two years.

Soil salinity negatively affects soil aggregation, structure, infiltration, and salts may be toxic for crops. It's important to remember that soil salinity is not the same as sodic soils. The difference is in the type of salts present in the soil. Sodicity means higher sodium content, and general salinity includes calcium, magnesium, chloride, and carbonate accumulation. Common techniques to deal with these conditions include washing salts away and applying gypsum. When water for irrigation is available, applying large quantities of water help leach salts away from the root zone. However, the constant application of irrigation water or the poor quality of it can help build up the salt accumulation. Therefore, the efficacy of this method will greatly depend on the quality of water. The application of gypsum is done to reduce the effect of sodium. The calcium contained in gypsum replaces the sodium adhered to the colloids, which then reacts with the sulfur creating soluble sodium sulfate in the soil solution that is easily leached away. Soil test reports include salinity obtained through measuring the electrical conductivity of the soil sample. Sodicity is obtained by comparing the concentration of sodium with the total CEC.

### Leaching requirement example

To efficiently leach salts away, the soils profile should be wet enough for water to drain and carry salts away. The following are used to calculate the leaching requirement:

- $LR = EC_w / ( 5xEC_c - EC_w)$
- $WR = ET / ( 1 - LR)$

where LR stands for Leaching Requirement and the result has no unit it is a factor, $EC_w$ is the electrical conductivity of water to be used (in dS/m), and $EC_c$ is the desired electrical conductivity

to achieved or the threshold that the crop can handle. In the second equation WR is the water required to leach salts away, and the ET represent the evapotranspiration of the area which means the total moisture being lost through evaporation and transpiration that has to be compensated for to achieve and optimal salt flush (in mm/day).

**Example**

There is a hotel in a dry region of the western territory of Costa Rica, where they are having problems with their gardens. The soil and water were sent for analysis, and they obtained that their soil has a ESP of 10% and an EC of 5 dS/m. And their water turns out to have an $EC_w$ of 1 dS/m. They decided to work better with plants that can tolerate up to $EC_c$ of 1 dS/m in the soil, but first they have to determine the water requirement to maintain the soil in the 1 dS/m range. If the ET of the area is 6 mm/day, help them calculate how much water they should apply per day through irrigation.

1. Obtain the Leaching Requirement factor:

$$LR = (1\ dS/m) / (5{\times}1\ dS/m - 1\ dS/m)$$

$$LR = 0.25$$

2. Calculate the Water Requirement per day:

$$WR = (6\ mm/day) / (1 - 0.25)$$

$$WR = 8\ mm/day$$

**Result:** The recommended water requirement is 8 mm/day to maintain optimal growing conditions for their plants. Because they have an ESP < 15%, they don't have sodium related problems, therefore, the application of gypsum is not critical.

## Gypsum requirement example

Gypsum requirement can be calculated with the following equation:

- Gypsum requirement (ton/ha) = Na content (cmol/kg) x 4.5

**Example**

A farm in Guatemala is having problems growing crops. Soil samples were submitted for analysis and the results showed a ESP of 18% and a CEC of 20cmol/kg. They decided to apply gypsum to

improve their soil quality but need help calculating the total requirement. Help them solve the problem.

1. Calculate the sodium content:

$$Na\ (cmol/kg) = Total\ CEC \times ESP$$

$$Na = (20\ cmol/kg) \times 0.18$$

$$3.6\ cmol\ Na / kg$$

2. Calculate the gypsum requirement:

$$Gypsum = (3.6\ cmol/kg) \times 4.5$$

$$16\text{-ton Gypsum} / ha$$

**Result:** they need to apply 16 tons of gypsum per hectare.

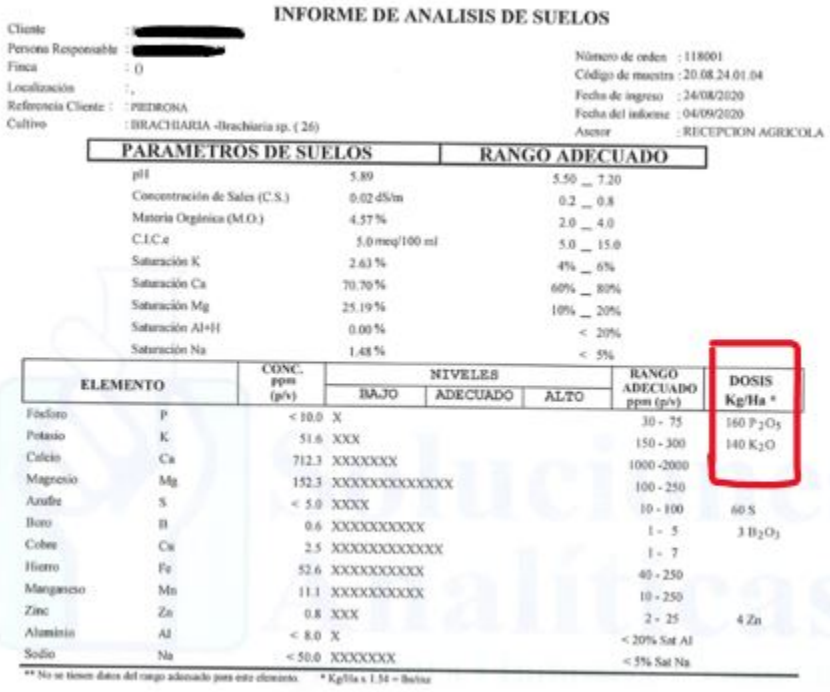
## THIRD: Make fertilizer recommendations

Fertilizer application is an alternative solution to compensate for nutrient deficiencies. They can be applied to build up the soil nutrient pool up to a critical threshold, to compensate for the nutrient mining done by the crops, or a combination of both. It is important to remember that over application of nutrient may result in luxury consumption by the crop, which results in toxicity and can be as detrimental as the deficiency of such nutrients. Therefore, it becomes vital to correctly interpret the nutrient levels and apply fertilizing products accordingly. Organic derived fertilizers contained lower levels of nutrients compared to synthetic fertilizers, but they can also help improve microbial activity and provide the benefits of soil organic matter. Conversely, synthetic formulas are intended to provide higher rates of nutrients and make them available more easily compared to organic products. Bulk blended fertilizers contained raw particles of different materials, in which each particle provides a different element. These tend to be cheaper but nutrient distribution is not as even and effective as chemical formulas can be. Granular fertilizers contained particles of equal size and chemical composition that are obtained by mixing together raw materials through chemical reactions. These required some extra processing and prices may be higher, however, they ensure that each particle contains an equal amount of nutrients, providing a more even application. It is on the farmer's judgement and accessibility the preference and acquisition of one over the other.

### Nutrient ratio example

Sometimes the nutrient ratio to apply is given in the soil test report, however, this is not always the case. The nutrient ratio indicates the proportion of NPK in the product to apply. For example, a 15-15-15 fertilizer has a ratio of 1-1-1, and the ratio 18-6-12 is 3-1-2. This helps decide on the product to apply and provide guidance when a custom formula is being created.

In this picture we can see the soil test report from a dairy farm in Guatemala. Soil in the region is derived from volcanic ashes and tends to have acidity problems due to high precipitation rates in the region. The results inside the red box show the required nutrients needed to bring the soil to an 'adequate' or optimum level, this means above deficiency.



INFORME DE ANALISIS DE SUELOS

Cliente : [redacted]
Persona Responsable : [redacted]
Finca : ()
Localización : ,
Referencia Cliente : PIEDRONA
Cultivo : BRACHIARIA -Brachiaria sp. ( 26)

Número de orden : 118001
Código de muestra : 20.08.24.01.04
Fecha de ingreso : 24/08/2020
Fecha del informe : 04/09/2020
Asesor : RECEPCION AGRICOLA

| PARAMETROS DE SUELOS | | RANGO ADECUADO |
|---|---|---|
| pH | 5.89 | 5.50 _ 7.20 |
| Concentración de Sales (C.S.) | 0.02 dS/m | 0.2 _ 0.8 |
| Materia Orgánica (M.O.) | 4.57 % | 2.0 _ 4.0 |
| C.I.C.e | 5.0 meq/100 ml | 5.0 _ 15.0 |
| Saturación K | 2.63 % | 4% _ 6% |
| Saturación Ca | 70.70 % | 60% _ 80% |
| Saturación Mg | 25.19 % | 10% _ 20% |
| Saturación Al+H | 0.00 % | < 20% |
| Saturación Na | 1.48 % | < 5% |

| ELEMENTO | | CONC. ppm (p/v) | NIVELES BAJO | NIVELES ADECUADO | NIVELES ALTO | RANGO ADECUADO ppm (p/v) | DOSIS Kg/Ha * |
|---|---|---|---|---|---|---|---|
| Fósforo | P | < 10.0 | X | | | 30 - 75 | 160 $P_2O_5$ |
| Potasio | K | 51.6 | XXX | | | 150 - 300 | 140 $K_2O$ |
| Calcio | Ca | 712.3 | XXXXXXX | | | 1000 -2000 | |
| Magnesio | Mg | 152.3 | XXXXXXXXXXXXX | | | 100 - 250 | |
| Azufre | S | < 5.0 | XXXX | | | 10 - 100 | 60 S |
| Boro | B | 0.6 | XXXXXXXXXX | | | 1 - 5 | 3 $B_2O_3$ |
| Cobre | Cu | 2.5 | XXXXXXXXXXX | | | 1 - 7 | |
| Hierro | Fe | 52.6 | XXXXXXXXXX | | | 40 - 250 | |
| Manganeso | Mn | 11.1 | XXXXXXXXXX | | | 10 - 250 | |
| Zinc | Zn | 0.8 | XXX | | | 2 - 25 | 4 Zn |
| Aluminio | Al | < 8.0 | X | | | < 20% Sat Al | |
| Sodio | Na | < 50.0 | XXXXXXX | | | < 5% Sat Na | |

** No se tienen datos del rango adecuado para este elemento. * Kg/Ha x 1.54 = lbs/ac

Soil test report example. Picture by: Arturo F.

To decide in which fertilizer to apply, obtaining the recommended nutrient ratio can help. To do this follow the steps:

1. Obtain the recommended rate of each nutrient by subtracting the actual level from the desired 'optimum' level (Rate = optimum – actual). In this case the lab already reports this result (we just have to transform it into our desired units).

160 kg P2O5 ha-1 = 142.51 lb P2O5 acre-1

140 kg K2O ha-1 = 124.60 lb K2O acre-1

2. Nitrogen is not commonly analyzed in this kind of tests because of its mobility and ease to leach and volatize. Therefore, tissue analysis is preferred, and nitrogen fertilization attempts to compensate for the biomass produced in certain are. The image shows the crop here is *Bracharia,* and a commonly accepted rate of N for this is 100 kg N ha-1.

   100 kg N ha-1 = 89 lb N acre-1

3. The ratio is obtained by dividing the total required of each nutrient by the smallest value, in this case N.

   89 lb N acre-1 / 89 = 1

   142.51 lb P2O5 acre-1 / 89 = 1.6

   124.60 lb K2O acre-1 / 89 = 1.4

The recommended ratio here will be 1 – 1.6 – 1.4. Knowing this ratio, it is possible to choose from commercial formulas that best fit the needs or to mix fertilizing materials to supply the required nutrients.

## Fertilizing recommendation examples

The process of balancing soil nutrients consists in bringing deficient nutrients up to an optimal threshold. The following videos provide a step by step in the process and help understand how to make fertilizer recommendations. When creating a fertilizing mix, it is important to consider the compatibility of the materials to avoid precipitation or insolubility of some nutrients.

**Video 1: Calculate the nutrient ratio**

**Video 2: Calculate how many bags of fertilizer we need**

**Video 3: Create your own NPK fertilizer**

**Extra:**

Watch the videos in the online version of this text: https://iastate.pressbooks.pub/isudp-2025-201/chapter/soil-input-recommendations/

PART VIII

# Soil Erosion

CHAPTER 41

# Soil Erosion

**Amber Anderson**

## Learning Objectives

- Describe the impacts of erosion
- Outline the process of erosion
- Identify soil erosion indicators on the landscape

**Keywords:** Wind, water, gully, rill, sheet, saltation

## Process

Erosion is the removal of the upper layer of soil or topsoil. Since that layer tends to have higher organic matter and nutrients, erosion of the surface layer can cause significant negative effects on the soil for future crops as well as runoff. An inch of soil may take a thousand years to build, but could be removed in one rainstorm. Areas with shallow bedrock (R horizon) are particularly sensitive, as erosion may lead to a loss of the area for agriculture.

Erosion requires three main steps: detachment, transport, and deposition. We separate erosion into two major categories by the force that transports the soil particle.

## Detachment

Not all soils or soil particles are equally susceptible to erosion. Sand may be easy to pick up, but is heavier to carry, so tends to stay closer to the source. Clay is hard to detach, but once separated, can stay in the air or water column for significant periods of time. Silt is generally considered the most erodible particle, as it is both reasonable to detach and carry.

Well aggregated soils are also considered less erodible-since the force would have to either break up the strong aggregate, or transport the whole aggregate.

## Transport by Wind

> Watch this video for more information: https://www.youtube.com/watch?v=PQmon7Rj6ns



Wind erosion during sugarcane harvest, Costa Rica, Spring 2019.
[Photo Credit: Amber Anderson]

## Transport by Water

> Watch this video for more information: https://www.youtube.com/watch?v=6n-7p89O_2c

## Observe from the video:

- When does the water slow down?
- When does the water appear more dirty/less dirty?
- What do you notice about the plants/plant roots? (soybean plants in particular)
- What else do you notice?

In Iowa, water is considered the dominant eroding force, but this does not mean that wind erosion is not occurring.

### Check it out!

The Daily Erosion Project is a model based upon the rainfall data received along with soil characteristics to estimate loss after a given storm. Find a watershed of interest and see how much soil they lost in a given storm.

## Shapes

### Gully



Gully formation near Ames High School. [Photo Credit: Amber Anderson]

Most noticeable, gully erosion appears as large channels being cut into the ground, looking like a stream. These are impassable with equipment due to size. If not stabilized, water plunging down the wall will continue to move up the hillslope. It is easiest to deal with before this point, but controlling water as high up on the slope as is feasible. Simply filling the gully with sediment or rock will not solve the issue.

## Rill

These are smaller channels, appearing more like fingers on the landscape. They can be destroyed by tillage-however, that is only destroying the evidence, not putting the soil back to the original condition. If the problem is ignored, future erosion will likely occur down the same path.

## Sheet

Least noticeable, this type of erosion takes a small layer equally off the soil surface.

> Watch this video for more information: https://www.youtube.com/watch?v=YElKtZY7sx8

# Deposition

As "what goes up comes back down" so does detached and transported soil need to be deposited at some point. Sometimes this is only a few inches, or it could be hundreds of miles away. Additional damage or costs may result at that point, from filling in ditches or lakes, damaging human lungs, or covering other infrastructure-requiring removal or treatment costs as well as the loss to the source. In some cases, the previous A horizon is buried, as in the videos below:

> Watch these videos for more information:
> https://youtu.be/QMiO_TdygOshttps://www.youtube.com/watch?v=esblbrFtA9k

### Key Takeaways

- Erosion can occur in a variety of ways, but always includes detachment, transport, and deposition
- Erosion has significant negative impacts on soil properties and productivity, with potential costs of clean up as well.

CHAPTER 42

# Soil Erosion Factors and Calculations

**Amber Anderson**

## Learning Objectives

- Discuss factors influencing differences in rates of loss
- Estimate erosion loss under a given management scenario
- Predict how management changes could increase or decrease potential erosion losses

**Keywords**: soil erosion

## Estimating Erosion

If the removal or deposit is clearly visible, as may be the case in gully, losses could be roughly estimated based upon the area removed. Generally, the losses are more subtle.

Estimating erosion after it has occurred, while may be needed to understand the extent of the damage and prevent future damage, is often too late.

Ideally, we would like to know the potential impact of a change before the erosion occurs. We use predictive models like the Universal Soil Loss Equation, or updated Revised Universal Soil Loss Equation (one or two) to predict the erosion under a given scenario. The major differences between these three equations is how conditions are calculated-with the first using one value for the year while updated equations divide up the year to recognize that conditions are not uniform throughout the year.



Soil core from central Iowa showing a shallow depth to C horizon (and calcareous conditions) very shallow due to significant past erosion. [Photo credit: Amber Anderson]

**<u>This equation only estimates rill and sheet erosion due to water.</u>**

$$A = R \times K \times LS \times C \times P$$

Where:
**A**= estimated erosion in tons per acre per year
**R**=rainfall erosivity value
**K**=soil erodibility (between 0.05 for sandy soils and ~0.35-0.4 for more silty materials)
**LS**=slope factor accounting for both length and steepness
**C**=cropping factor
**P**=other practices
**T**="Tolerable" erosion

**A note on T factor:** This is set not at replacement rate, that is much smaller. It is what the soil could lose per year and maintain productivity for a medium term-it shouldn't be considered sustainable for long-term productivity.

## Key Takeaways

- USLE is one tool to estimate losses anticipated (water erosion from sheet and rills) under a current or proposed management scenario

CHAPTER 43

# Erosion Control Strategies

**Amber Anderson**

## Learning Objectives

- Describe soil erosion control strategies
- Differentiate between erosion control strategies for wind, water, and other factors

**Keywords**: erosion control strategies, soil stability, soil health

The main goals of erosion control strategies are simple-control either detachment or transport of soil. Specifics are dependent upon the situation, as what works in one location may not work for another.

## Soil Health

Maintaining soil health increases resilience to erosive forces. Aggregate stability-as shown in the video below, is one of the factors impacting erosion. If aggregates stay together, water erosion will only take place if there is enough force to move the whole aggregate, rather than the single particle.

> Watch this video for more information: https://youtu.be/k18VKZ6fulM

## Wind Erosion Control

Major strategies to control wind erosion include protecting the soil from initial detachment, or slowing the wind so it cannot detach or carry the sediment. These may look different depending upon the situation, but a few examples might be windbreaks, eliminating or decreasing tillage, or adding cover crops or a perennial cover.

### Windbreaks

A common feature around sensitive sites, like farmsteads or high value crops, is a windbreak. Installed up-wind from the location, the area protected is approximately 10x the height of the windbreak downwind of the feature. Closest to the windbreak is most protected and protection decreases with distance away.

#### Windbreak resources

- Field windbreak[1]
- Farmstead windbreak[2]

## Water Erosion Control

A variety of techniques can be utilized for decreasing water erosion. Main principles are the same, to control detachment and/or slow down the water so it is unable to carry the sediment.

1. NRCS. (n.d.). Field windbreak. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/land/forests/agroforestry-systems/field-windbreak
2. NRCS. (n.d.). Farmstead windbreak. https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/land/forests/agroforestry-systems/farmstead-windbreak

## In agricultural fields







Soybeans planting into standing rye cover. The rye was planted in the early fall starting growth then and continuing in the early spring to protect the surface over the fall and increase biological activity/organic matter. This rye was terminated near the soybean planting time.

Other practices might include terraces, that break up the slope length allowing infiltration. Waterways, protecting the path of the water off the field instead of allowing rill or gully erosion.

## Roads



New construction is particularly sensitive to erosion, this disturbed shoulder off of I-35 near Ankeny is using a few techniques to control erosion-straw waddles and straw to help grass seed establishment. [Photo Credit: Amber Anderson]



This road ditch in Uganda has complete covered the area water would run with cement and rocks so it cannot erode and undermine the road. [Photo Credit: Amber Anderson]

## Construction sites



As the perennial cover of grass gets established next to the new Ames High School, these black strips are used to slow water and stop sediment moving down the hill. [Photo credit: Amber Anderson]



During construction, this black bag was used to capture sediment and any other materials that would have otherwise moved into the storm sewer and water system. [Photo credit: Amber Anderson]



This mat is used to help protect the soil surface and keep seed in place during establishment. [Photo credit: Amber Anderson]



This reinforced mat is being used on a steeper part of the landscape while grass is being established that will stabilize the area for the long term. [Photo credit: Amber Anderson]



After construction of the business building addition, hydromulch was used to protect the surface and help establishment of the new grass seed. [Photo credit: Amber Anderson]





Runoff off of construction site on ISU campus

PART IX

# Soil Fertility

CHAPTER 44

# Nutrient Basics

**Amber Anderson**

## Learning Objectives

- Compare and contrast macro vs micronutrients
- Relate mobility in plant to expected deficiency symptom location
- Identify potential deficiency patterns on the plant or in the field

**Keywords**: macronutrients, micronutrients, nutrient deficiency

## Macronutrients vs micronutrients

While both macro and micronutrients are required for plant growth, there are needed in differing quantities. Macronutrients are needed in larger quantities and are usually involved in the structural components of plants. Micronutrients are just as required for healthy plant growth but needed in smaller quantities. They are usually components of enzymes or metabolic functions. A micronutrient deficiency may be corrected with a few pounds per acre, while a significant macronutrient deficiency will likely take significantly more fertilizer.

## Deficiency symptoms vs hidden hunger



A plant may not appear clearly nutrient deficient immediately, but may grow or yield poorly. Deficiency symptoms likely indicate a significant issue that should be addressed, but it may be too late to obtain the full yield of an annual crop this season. Deficiency symptoms can include a variety of visual abnormalities, including yellow striping, stunted plants, purple coloration, malformed structures, or others depending upon the plant and nutrient.

## Deficiency vs toxicity

Both too much and too little of a nutrient can significantly impact plant growth. At excessive levels, too much of a nutrient accumulating in tissues can cause damage, or interfering with uptake of other nutrients. This can be more significant of an issue at low pH values, when metals are more soluble.

## Mobile vs immobile



A nutrient can be mobile in the plant and the soil. If a nutrient is immobile in the plant, it can't be moved to new growth if the plant runs out, where as a mobile nutrient couple be transported within the plant to the area of most need. Therefore, a mobile nutrient deficiency will appear in the older growth, where an immobile nutrient deficiency will first appear in the new growth. If a nutrient is immobile in the soil, a root needs to grow to it rather than relying on water to help carry it to the root. Therefore an immobile nutrient deficiency may occur in conditions of poor root growth, such as a cool, wet Midwest US spring.

### Examples

- View a table of nutrient availability in the plant vs in the soil here

### Remember:

Don't assume that a nutrient deficiency means a soil deficiency. Sometimes soil or plant conditions simply don't allow for sufficient uptake, like iron in a high pH soil. Iron chlorosis is not effectively solved by adding more iron. Depending upon the plant or conditions, management options could include foliar application, adjusting the pH, or simply choosing a more tolerant crop.

## What to look for in the field

Patterns can be helpful in determining or narrowing out potential diagnoses. A strip of yellow corn across a field or deficiency symptoms matching the width of the application equipment could be associated with equipment malfunction. Straight lines are unusual in nature, so could point to a human interaction, such as nutrient or chemical application equipment, change in plant hybrid selected, or past fenceline/treatment change.

> Watch this video for more information: https://youtube.com/shorts/H7M-yEPJnTc

Alternatively, an area on a steep slope showing a deficiency may be associated with erosion and resulting lower organic matter, significantly different pH value (as is common across calcareous parent materials like in the central US), or some other soil factor. Using the soil map and further soil testing can help problem solving, and may result in multiple issues being discovered.

### Key Takeaways

- Nutrients have a variety of properties that influence when and where a deficiency may appear along with how much may be needed to address the deficiency.
- Challenging soil conditions may limit options for addressing the plant nutrient needs.

CHAPTER 45

# Phosphorus

**Amber Anderson**

## Learning Objectives

- Identify major pieces within the phosphorus cycle and factors impacting plant availability
- Explain potential impacts on the environment from contrasting management
- Recommend practices to decrease the environmental impact of phosphorus fertilization

**Keywords**: phosphorus, phosphorous in water

## Phosphorus Characteristics in Soil

There is a small amount of phosphorus in the soil solution and, therefore available to a plant at any point in time. Low total amounts in the soil and low solubility mean that the plant can lack sufficient phosphorus for growth, particularly in cool and wet spring conditions when Iowa's annual crops have a minimal root system exhibiting lots of branching. Availability can be impacted by soil pH, at both low or high ranges, as phosphorus can form calcium phosphates or iron phosphates. Due to low plant availability, mycorrhizal associations can be significant contributors to plant uptake for phosphorus.

Phosphorus fertilizers include animal manures, DAP (Diammonium phosphate) or MAP (monoammonium phosphate) are made by combining ammonia and phosphoric acid. Alternatively, mined rock phosphate or other unique materials such as guano.

## Role in Plant Growth

As a part of ATP, phosphorus is important for energy transfer within the plant. Therefore, stunted plants are expected, but purple coloring is also common.



[Photo credit: Lizzie Dykstra]



The top plant is from the center of a disturbed area (pipeline construction), the edge of disturbed area, and just outside of the disturbed area on the bottom. [Photo credit: Lizzie Dykstra]

## Phosphorus Loss

Phosphorus loss from Iowa soils or to Iowa water bodies is generally attributed to erosion of the entire soil rather than via water. Therefore, strategies to decrease loss or improve water quality focus on decreasing erosion rather than biological mechanisms for nitrate loss. Decreasing erosion, through decreasing tillage, increasing cover, buffer strips, increasing perennial cover on the landscape, decrease phosphorus loss to water bodies.

Additionally, livestock manure can be detrimental to local water quality, resulting in decreased use and function as can be seen in the photo below. Stream exclusion fencing, keeping livestock from wallowing in the water and adding manure, can decrease the risk to water quality. Application of manure should be incorporated, not applied to frozen ground when it would be more likely to run off, and should be set back from the stream or water body.

### By how much do practices decrease loss of N and P?

- Reducing Nutrient Loss-Science Shows What Works—See what expected decrease to N and P levels by potential practices.[1]

## Importance in Water Bodies

Significant water quality issues result from phosphorus enrichment, both at local and national scales. Nutrient contribution from the upper midwest contributes to the significant hypoxic or 'dead zone' in the US Gulf of Mexico. Eutrophication, or the nutrient enrichment of these water bodies causes excessive growth, and then excessive decomposition, which decreases oxygen in the water. Since organisms in the water need oxygen, this causes a collapse in the local ecosystem. Therefore, it is important to minimize loss from our soils and decrease impact on nearby water bodies.

### Nutrient Reduction Strategy

- Nutrient reduction strategy details here[2]

### Key Takeaways

- Phosphorus is limiting in many environments and must be carefully managed to ensure successful plants and environmental quality.


1. Iowa State University Extension and Outreach. (2019). Reducing nutrient loss: Science shows what works. https://store.extension.iastate.edu/product/Reducing-Nutrient-Loss-Science-Shows-What-Works

2. Iowa Department of Natural Resources. (n.d.). Nutrient reduction strategy. https://www.iowadnr.gov/environmental-protection/water-quality/nutrient-reduction-strategy

CHAPTER 46

# Nitrogen

**Amber Anderson**

## Learning Objectives

- Outline basic steps in the nitrogen cycle
- Identify potential sources of loss or transformation resulting in decreased available N in the soil
- Predict differences in loss of nitrogen under contrasting conditions.

**Keywords**: nitrogen cycle, nitrogen management, nitrate testing

## Importance of Nitrogen

Nitrogen is critically important to plant growth as it is a part of chlorophyll, nucleic acids (DNA), amino acids, and proteins. Therefore, a nitrogen-deficient plant will appear yellow with decreased growth. Despite being a major component of the air around us, nitrogen can regularly be a plant-limiting nutrient. Today, commercial nitrogen fertilizer production, known as the Haber-Bosch process, uses large amounts of energy to convert the nitrogen in the atmosphere to plant-usable forms. Previously, legumes and manures were used for nitrogen management within agricultural systems.



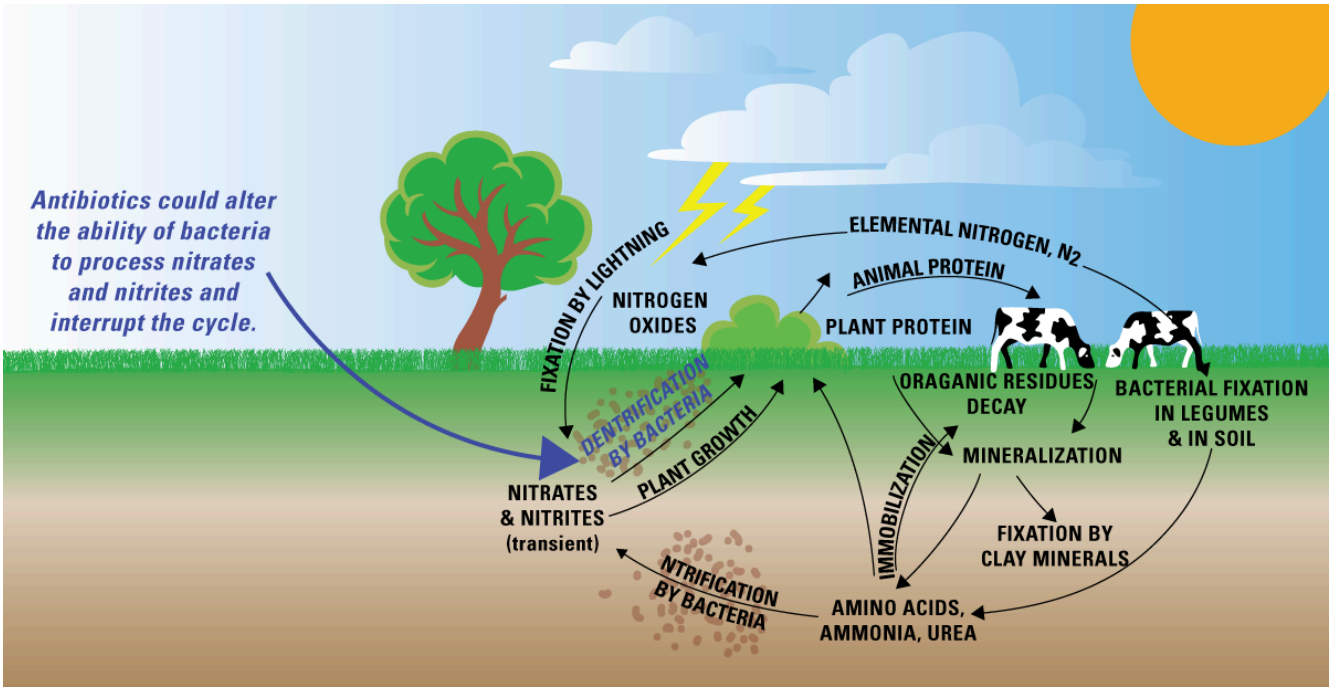
A corn field with a strip of grasses through it.

Nitrogen is a challenge for management due to its significant biological reactivity, interactions with soil, and potential negative impacts on human health and the environment. The US Environmental Protection Agency (EPA) has set a limit of 10 ppm (10 mg/L) of nitrate in its safe drinking water standard due to the potential negative health implications, such as blue baby syndrome. Environmentally, nutrient enrichment coming from the corn belt contributes to the dead zone in the gulf of Mexico.



Lower leaf of corn plant showing nitrogen deficiency symptoms

## Simplified Nitrogen Cycle




Simplified nitrogen cycle. [Image Credit: US Geological Survey]

## Transformations

- **Fixation:** $N_2$ gas converted to plant-usable form through either free-living or symbiotic organisms. Commercially or industrially, atmospheric nitrogen can be fixed using significant amounts of energy through the Haber-Bosch process. This nitrogen is added to the soil and/or plant available pool.
- **Nitrification:** N is biologically converted to nitrate ($NO_3^-$), which can be lost due to leaching.
- **Denitrification:** Nitrate ($NO_3^-$) to $N_2$ or nitrous oxide (greenhouse gas), usually occurs due to biological activity and anaerobic conditions, like could exist in a waterlogged soil. This is a loss from both the soil and available pool.
- **Immobilization**: Nitrogen removed from plant-available pool due to uptake by microbial tissues, so a short-term loss from the plant-available pool, but not a long-term loss.
- **Mineralization:** Organic nitrogen converted to plant-available nitrogen, the reverse of immobilization.
- **Leaching**: Nitrate (usually) lost due to moving through water and out of the system.
- **Volatilization:** Ammonia ($NH_3$) lost from the soil as a gas, like if anhydrous ammonia is applied to dry soil or with equipment that didn't successfully seal the furrow.
- **Ammonification:** N is converted to $NH_4^+$ form of nitrogen.

Note that microbial activity is a major component of many transformations, with soil conditions, such as low oxygen or warmer soil temperatures, change the types and rates of transformations present.

## Legumes and nitrogen management

Historically, legumes like alfalfa, beans, and peas, in combination with animal manures or composts, were used to add nitrogen or manage nitrogen in agricultural or horticultural settings. Many of these techniques are still used, based upon available resources.

## Nitrate testing

In Iowa, any nitrate remaining in August is assumed to be lost before the next cash crop would utilize it, so it is not regularly included in standard fall soil testing. In drier climates, this may not be the case, and fall or winter nitrate testing may occur. The spring soil nitrate test may be used after corn has begun its growth to determine if an additional side-dress application of nitrogen would be warranted.[1] Fall cornstalk testing could be used to assess if nitrogen was sufficient or likely in excess to determine future management. If still possible, a cover crop could be used to uptake the remaining nitrate and prevent it from leaching.

### Additional Nitrogen Cycle video

This video was developed by Dr. John Sawyer with ISU Extension: https://youtu.be/SVFywwreP0I

### Check it out!

- Check out the nitrogen rate calculator here[2]

1. Mallarino, A. (2022, June 7). Using the late spring soil nitrate test in 2022. ICM News. https://crops.extension.iastate.edu/cropnews/2022/06/using-late-spring-soil-nitrate-test-2022
2. Corn nitrogen rate calculator. (n.d.). https://www.cornnratecalc.org/

## Key Takeaways

- Nitrogen management is dynamic due to its biological reactivity
- Potential losses can occur to either air or water
- Biological transformations significantly impact the plant-available N

CHAPTER 47

# Potassium

**Amber Anderson**

## Learning Objectives

- Identify the function of potassium in the plant and potential deficiency symptoms.
- Define the concept of “luxury consumption”
- Identify under what conditions potassium deficiencies might be more likely

**Keywords**: potassium, luxury consumption, potassium deficiency

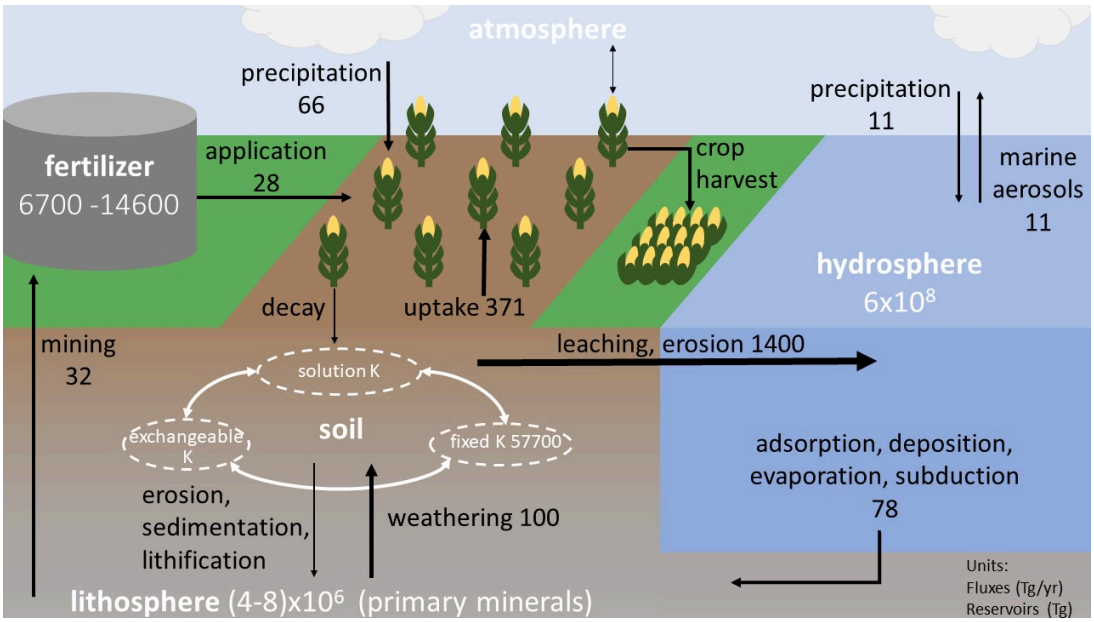
## Role in the plant

Potassium is contained in the sap rather than structural components of the plant. It is involved in water regulation, such as stomata opening and closing, as well as some enzymatic and energy reactions within the plant. Because of this function, deficiency symptoms may be more evident in hot and dry growing seasons.



## Potassium cycle

The primary location of potassium in soils are the primary minerals. Small amounts are held on the cation exchange capacity, and significantly less of that is available to the plant in the solution at one time. If the soil can’t supply potassium, fertilizer application would be required. Historically, materials like ‘pot-ash’, or ash from burned materials would be used for potassium enrichment.




Potassium cycle illustrated. Image Source: Compost Camel, CC BY SA

## Luxury consumption

Luxury consumption is the concept of plant uptake beyond plant needs. If the crop is harvested for grain, this may not be a significant issue. However, if a forage like alfalfa, or silage is produced, this would result in a higher export of potassium from the soil.



Potassium deficiency on soybean

## Deficiency symptoms

Deficiencies in potassium may be found in areas where the entire plant is removed, while green.

### Potassium and forage management:

- Soil potassium and alfalfa[1]

## Key Takeaways

- Potassium is important in water regulation within the plant
- Risk of potassium deficiency increases in areas where plants are harvested green and removed
- Symptoms may be more evident in hot and dry years

1. Leege, R. (2019, Oct 14). Alfalfa and potassium: It's complicated. Phys.org. https://phys.org/news/2019-10-alfalfa-potassium-complicated.html

CHAPTER 48

# Micronutrients

**Megan Blauwet**

## Learning Objectives

- Identify functions of micronutrients in the plant
- Match soil properties with potential deficiencies

**Keywords**: micronutrients, nutrient deficiencies

**Micronutrients** make up a small percentage of the overall plant, but are critical for growth. Most are used in enzymes rather than structural components of the plant.

Extreme cases, like extreme pH values, peat soils, or otherwise unusual conditions makes deficiencies more likely. Since deficiencies are resolved by small quantities per area, they may be added to other mixes or strategy that allows more effective spreading. Materials such as manure or composts may be used, depending upon analysis.

There are eight micronutrients that are essential for plant growth. These include boron, zinc, manganese, molybdenum, iron, copper, chlorine, and nickel. All micronutrients are needed in small amounts so when soils contain too much of them, toxicity can occur.

## Boron (B)

Boron is used in plants for germination, pollination, sugar transport, cell wall development, protein formation, and carbohydrate metabolism. Boron is one of the most common micronutrient deficiencies. Boron is most often limited in alkaline soils and oppositely can have toxic amounts in acidic soils. A deficiency in boron will affect the vegetative and reproductive growth of the plant.

Deficiency symptoms include chlorosis, death of buds/flowers, and death of new growth. A fertilizer most often used to add boron to the soil is sodium borate which contains around 10-20% boron.

## Zinc (Zn)

Zinc is a part of many enzymes in the plant that are used for metabolic functions. A lack of zinc will create problems with protein, carbohydrate, and chlorophyll formation. Deficiencies are most likely to occur in calcareous soils with low organic matter and high pH. Zinc has a relationship with phosphorus in the soil where too much phosphorus can result in Zn deficiency. Deficiency symptoms include striping of corn leaves or yellowing of leaves. Zinc sulfate is the most common fertilizer used to add Zn to soils.

## Manganese (Mn)

Manganese is an important micronutrient involved in critical functions in the plant such as photosynthesis, nitrogen assimilation, and respiration. Deficiency is most likely to occur in high pH soils and toxicity can occur in low pH soils. Manganese competes with iron in the soil so it is important to keep them balanced. The symptoms of Mn deficiency includes yellowing of leaves with wide green areas on the veins. Manganese sulfate is a common fertilizer added to soils that are deficient.

## Molybdenum (Mo)

Molybdenum is a part of enzymes that are used in nitrogen fixation, nitrate reductase (converting nitrate into proteins), and the conversion of inorganic phosphate to organic. Unlike most other micronutrients, molybdenum deficiencies occur in acidic soils. Toxic amounts of molybdenum in plants used to feed animals can be quite harmful. Since molybdenum is related to nitrogen functions in plants, deficiencies can look similar and result in yellowing of leaves and stunting of growth. Fertilizers that add molybdenum include sodium molybdate and ammonium molybdate.

## Iron (Fe)



Iron chlorosis on a tree in central Iowa

Iron is a part of many enzymes and is used for chlorophyll formation, cell division and growth, and oxygen transport. Iron deficiencies are found in soils with high clay content or high pH soils. Interveinal chlorosis is the most typical iron deficiency symptom. Iron added to the soil in fertilizers is often chelated iron which will be available for longer in the soil. A foliar spray of ferrous sulfate is also available and commonly used.

## Copper (Cu)

Copper is a part of enzymes critical for photosynthesis, respiration, and lignin production. Copper deficiencies are not very common in most soils but can be found in sandy soils or peat soils with very high organic matter. Plant deficiency symptoms include slight yellowing of leaves and leaf tip twisting or death. Copper sulfate is a common fertilizer applied to fix copper deficient soils.

## Chlorine (Cl)

Chlorine is used in stomata regulation, osmotic regulation, and disease resistance. Chlorine can be problematic in arid regions due to it largely being found in salt forms in soil. Chlorotic or necrotic spots on leaves and wilting are common deficiency symptoms. Potash (KCl) fertilizer is often applied for its potassium, but it also provides chloride to the soil.

## Nickel (Ni)

Nickel is the most recently discovered plant micronutrient. Its function in the plant is as a cofactor for the conversion of urea into a plant available form. Nickel deficiency in plants is very rare but can appear as necrosis of leaves (due to buildup of urea) and is most likely to be found in high pH soils. If a soil is low on nickel, nickel sulfate fertilizer can be added.

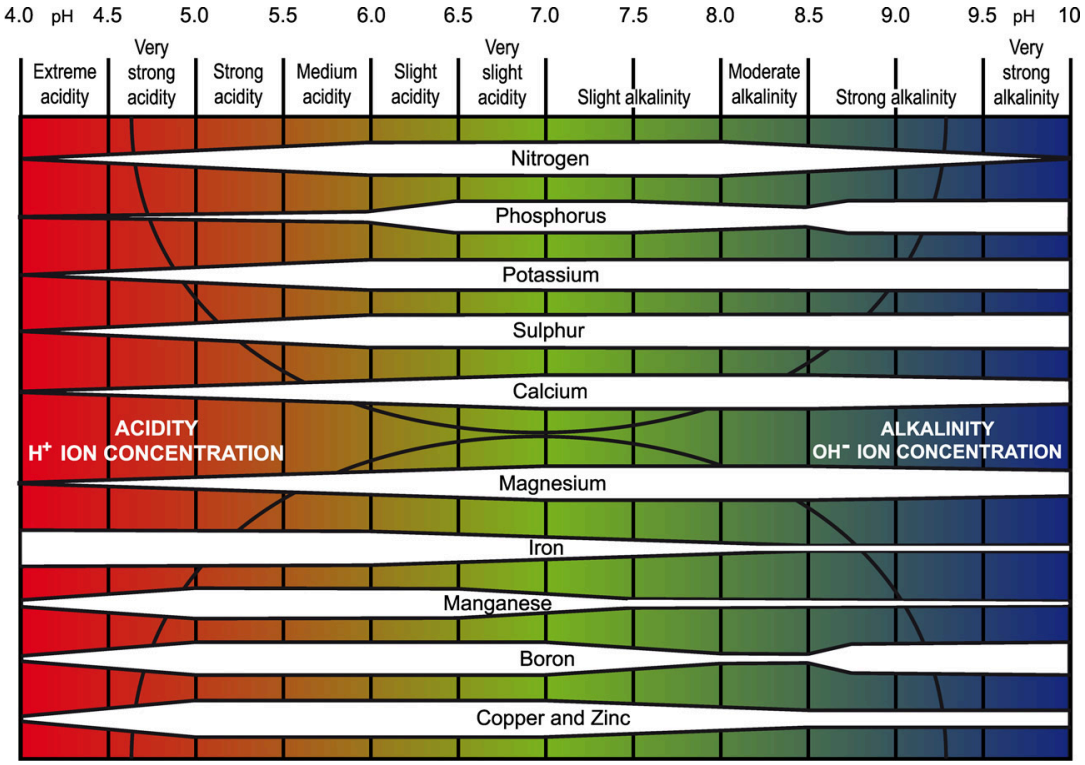



Figure showing pH influence on plant nutrient availability. [Image Source: Potash Development Association]

## Key Takeaways

- Micronutrients are essential to plants but needed in small amounts.
- There are 8 essential plant micronutrients and most are a part of enzymes or used in metabolic functions.

PART X

# Soil Organisms and Organic Matter

CHAPTER 49

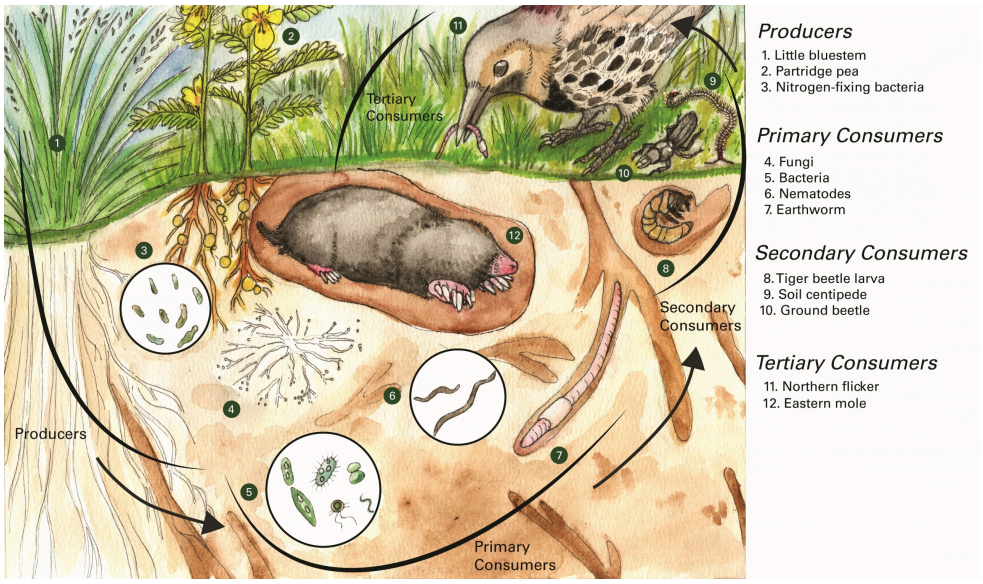
# Soil Life

**Cole Dutter**

## Learning Objectives

- Explain the importance of soil life
- Compare major classes of organisms found in the soil
- Identify interactions of other soil properties and organisms
- Predict impacts of a management decision on soil organisms

**Keywords:** ecosystem engineers, symbiosis, rhizobacteria, mycorrhizae, rhizobium




Soil Life is important for the breakdown and stabilization of organic matter, breakdown of toxic compounds, nitrogen fixation and nutrient cycling. [Image Credit: *Illustration by Madeline Schill, 2021,* in Soils-Iowa's Nature Series]

## Primary Producers

Primary producers is the term used for organisms that use energy from the sun to create organic molecules (autotrophs). Vascular plants are the most commonly known form of primary producers, however in the soil, other primary producers are mosses, algae, and certain photosynthesizing bacteria. Primary producers hold a central role in soil due to their importance to synthesize and produce new compounds and introduce them to the soil environment. In other words, they are the base of the food web.

## Primary Consumers

Primary consumers are organisms that feed off of the primary producers. Some may try to term these organisms herbivores, but that is only a portion of the group considered primary consumers. Herbivores are organisms that eat live plants and contain parasitic nematodes, insect larva, ants, and larger vertebrates. Detritivores are organisms that consume debris from live tissue. Detritivores include larger mesofauna: springtails and mites. A third group is the saprophytic microorganisms. These microorganisms consume dead tissue and include bacteria and fungi. These consumers' purpose is to break down (decompose) plant and animal tissue and begin to facilitate the cycling of nutrients.

## Secondary and Tertiary Consumers

Secondary and tertiary consumers are the predators of the soil, they feed off of other consumers. These consumers include bacteria, fungi, and larger fauna considered carnivores (centipedes, nematodes, snails, etc.). This group can also contain parasites of other animals. This group is titled after the old "food chain" paradigm, thus we distinguish between secondary and tertiary consumers. In the newer paradigm of the "food web" there is less distinction between these two groups. This group helps cycle the nutrients that are stored in the primary consumer group.

## Ecosystem Engineers

Ecosystem engineers are larger animals that are capable of altering the physical environment that influence other soil fauna habitat. In the Midwest, these are primarily burrowing animals such as ants, worms, or gophers. These animals affect air and water movement through the soil, as well as create channels for plant roots.

## Not all earthworms help the soil: Check out this study!

- *Invasive earthworms erode soil biodiversity: A meta-analysis*

# Producer Consumer Symbiosis

> Watch this video on YouTube: Ectomycorrhizae video

> Watch this video on YouTube: Endomycorrhizae video

Symbiotic relationships occur between the plants and microbes because they are both benefiting from each other. The plant is able to provide a food source and home for the microbes and, in exchange, the microbes provide the plant with nutrients it requires.

Soil fungi that have formed symbiotic relationships with plants is one of the most economically important groups of soil organisms. **Mycorrhizae** have been studied for benefits such as increased drought tolerance and increased phosphorus uptake in crops.[1] Mycorrhizal fungi also help soil structure by contributing to aggregation through the production of glomalin.

**Rhizobium** or Bradyrhizobium bacteria species are best known for their relationships with legumes. These species are not generalists but are either host specific or have a range of hosts, however they do not inoculate all legume species. These species are responsible for the root nodules on legumes that fix nitrogen. Fixing nitrogen is a critical function because it takes nitrogen from the air and makes it available for the plants to use.

**Rhizobacteria** is a term for the bacteria that have adapted to living along the root surface. These species are the most common symbiosis, yet are seldom studied. The root surface becomes so encrusted with bacteria that little soil actually interacts with the root without some intervening microbial influence. These species assist in cycling nutrients near the root, including nitrogen.

1. Cheng, S., Zou, Y-N., Kuča, K., Hashem, A., Abd Allah, E.F., and Wu, Q-S. (2021). Elucidating the Mechanisms Underlying Enhanced Drought Tolerance in Plants Mediated by Arbuscular Mycorrhizal Fungi. *Front. Microbiol. 12*:809473. https://doi.org/10.3389/fmicb.2021.809473

Rhizobium are the face of nitrogen fixation yet Rhizobacteria also help supply nitrogen to the plant as well.

There are also pathogenic species as well! Sudden Oak Death is a Phytophthora species that kills trees. Named for the fact that early victims of this disease were oaks, this species can also prey on agriculturally important species such as Almonds. Sudden Death Syndrome is caused by a Fusarium species and is common in soybeans. Phytophthora and Fusarium are two genera that contain many diseases that attack economically important plants. Examples include: damping off disease, root and stem rot, crown rot, fusarium wilt, and fruit rot. These diseases are commonly controlled through crop rotation and planting resistant varieties.

## Management and Soil Life

Soil life, in general, needs two things to thrive: minimized disturbances and an adequate food source. In terms of management this means that practices that increase soil organic matter, decrease erosion, and increase soil structure are the key to increasing microbial communities and thus nutrient cycling. This can take many forms but there are two easy management practices that fulfill this: no-till and cover crops. Generally speaking, it can be said that "life creates life." One interpretation of this is that the more plants there are on the ground, the more microbial activity there is in the ground. In California, farmers are often concerned with weeds competing for water with the crop. Which leads to the implementation of strip spraying (pictured below).




Removing the plants around the trees may reduce the amount water used, but it also reduces the

amount of nutrients cycled near the tree in the early years of the orchard. As a consequence of this, many nutrients need to be applied either by pelletized fertilizer or foliar application. Similarly cover crops may cost the farmer a little more, but the plants contributions to microbial food sources or food complexity is important for a sustained robust microbial community.

Soil aggregation, facilitated by no-till agriculture, is not simply for better drainage and less erosion. Soil aggregation is important for niche complexity within the soil environment. Niche complexity allows for community complexity. Soil life, much like all forms of life, is not homogenous. Certain microbes may do well in saturated soils, others like drier spaces. A stable aggregate allows for the microbes to find their niche, the moisture desiring microbe will colonize the outside of the aggregate while the other will colonize the interior of the aggregate.

Disease pressure in the soil can be tricky to manage, however, one of the best methods to simply manage it is to rotate crops or plant resistant varieties. Soil fumigants can be used but commonly are expensive and difficult to employ. In California, the threat of nematodes have caused farmers to fumigate their fields with methyl bromide. This procedure was effective for two reasons, the farmers deep rip the field to open up the soil and the soil texture is sand to sandy loam. This allowed for effective use of the fumigants. Methyl bromide has now been phased out and farmers are struggling to find effective fumigants for the soil borne diseases. The new fumigants are targeted towards specific pests within the soil and are not generalists. While farmers complain about the ineffectiveness of the new fumigants, the overall effect will be for a healthier soil.

## Optional Supplemental Resources

There is so much information about soil organisms extending well beyond what can fit into a single introductory course. If you want to optionally learn more, check out the below links that interest you.

- Dead stuff: The secret ingredient in our food chain – John C. Moore video
- Slime Molds Remember — but Do They Learn? Magazine article
- The Beautiful Intelligence of Bacteria and Other Microbes magazine article
- At Tiny Scales, a Giant Burst on Tree of Life magazine article (2015)
- What a Newfound Kingdom Means for the Tree of Life magazine article (2021)
- Can soil microbes adapt to different climates and regions? Blog post
- Where Does the Smell of Rain Come From? Video about actinomycetes & geosmin by It's Okay to be Smart

- What's the largest terrestrial organism? Blog post
- This Underground Economy Exists in a Secret Fungi Kingdom video
- Soil Ecology clay animations youtube playlist
- Mycorrhizae and their Partner Plants clay animation video
- How trees secretly talk to each other – BBC News video about how trees communicate through mycorrhizae
    - Note: Research on this subject is ongoing. Whether trees are really "talking" or just signaling each other remains uncertain. It's also uncertain whether the trees intend to communicate, or if the mycorrhizae are just bartering resources on their behalf.
- The Secret Language of Plants magazine article
- The secret language of trees – Camille Defrenne and Suzanne Simard TED Ed video
- A close-up of creatures living beneath the soil – Deep Down & Dirty: The Science of Soil – BBC Four video
- A World in One Cubic Foot (ebook) nature photography compilation of organisms found in one cubic foot of different ecosystems, both aboveground and in soil
- The Living Soil: How Unseen Microbes Affect the Food We Eat (360 Video)
- Biological soil crust Wikipedia page
- BIOLOGICAL SOIL CRUSTS technical reference pdf from the Bureau of Land Management, very detailed
- A Field Guide to Biological Soil Crusts of Western US Drylands pdf from the Bureau of Land Management
- Biological Soil Crust of Southeast Utah (US National Park Service) website
- NRCS Soil Health website
- What is your definition for soil health? website
- What is Soil Health and How Can We Improve It? | Integrated Crop Management Iowa State University extension website
- North American Project to Evaluate Soil Health Measurements website by the Soil Health Institute
- Comparing Microorganism Size Under the Microscope video
- How do soil microarthropods affect crop production? Blog post on meso-organisms

## Key Takeaways

- Soil Life is important for a variety of reasons: breakdown and stabilization of organic matter; breakdown of toxic compounds; nitrogen fixation; and nutrient uptake and cycling
- Mycorrhizal associations with plants influence drought tolerance, nutrient uptake, and soil structure
- Management effects soil life in three ways: (1) food sources, (2) disturbances, and (3) disease cycles

CHAPTER 50

# Soil Organic Matter

**Amber Anderson**

## Learning Objectives

- Discuss importance of organic matter in the soil
- Identify mechanisms of addition or loss
- Predict a management change's impact on soil organic matter

**Keywords:** humus, organic matter

## Carbon cycle

Carbon dioxide is all around us, but plants convert that carbon into organic forms and remove it from the atmosphere. The soil is a significant storehouse for previous generation's carbon, in a variety of different forms.

## Organic matter

The term 'organic matter' is used to refer to things consisting of organic carbon-so anything that was alive. However, not all of these components are equal when considering function in soil. Some materials break down rapidly, releasing nutrients within a few months or years, while some carbon contained in organic structures have been in the soil for hundreds of years.

## Impact on soil properties

Darker soil colors generally correlate to higher levels of organic matter in the soil. Organic matter is also

helpful in other soil properties, such as nutrient and water holding capacity, resistance to compaction, and soil structure.

### Check it out!

- Check out the NRCS discussion on Organic Matter value in soil here
- Carbon cycle

## Decomposition

Decomposition rates vary based on soil conditions. As you make the environment more favorable for various microbes, decomposition will increase. Therefore, the most significant deposits of organic material are found where decomposition is slowed or stopped, but plant growth or other addition still occurs. One place might be a wetland-where anaerobic conditions slow decomposition, but water-tolerant plant species or even organisms like mosses are adding to the carbon pool.

- **Oxygen:** Anaerobic conditions decrease microbial activity and efficiency, so decomposition slows down significantly in these circumstances.
- **Food source:** In addition to being present, the food source will influence the rate of decomposition. For example, materials with large amounts of carbon per unit nitrogen-like wood-are harder to break down than fresh grass clippings.
- **Temperature:** Microbial activity, and therefore decomposition, is generally highest in the moderate temperatures.

## Organic Matter Accumulation in the Rainforest



Organic matter accumulation in the tropical rainforest. [Photo Credit: Arturo Flores]



Waterlogged soil in Costa Rica. [Photo Credit: Arturo Flores]

The first picture shows a thick layer of leaves accumulated on the soil. The exuberant vegetation is constantly growing throughout the year and rarely reduces its biomass production. The second picture shows how soils tend to be underwater when high precipitation events occur in a short period of time. It is possible to see how the organic matter is submerged with little to non-decomposition at all. High environmental humidity and waterlogged soils have low decomposition rates as microbial activity is limited. Also, the constant accumulation of new materials buries the old materials, and the process of decomposition starts again. However, it is important to know that although the soil might appear to have a high organic matter content, this is not completely true. Of more importance is the active soil organic matter, which has already been decomposed to some degree and actively contributes to the soil properties, such as in CEC and physical aggregation.

## For further thought:

Think about a compost pile. What happens when only leaves are there? What happens if you add a pile of fresh greens (or leave them out on your counter/in the bottom of the fridge for too long)?

## Optional Supplemental Resources

There is so much more to learn about soil organic matter than can possibly fit into an introductory course. Optionally check out any of the resources below that interest you to learn more.

- Soils: Our ally against climate change video
- The Global Carbon Cycle: Crash Course Chemistry #46 – good intro video about the carbon cycle
- The Hydrologic and Carbon Cycles: Always Recycle! – Crash Course Ecology #8 – introductory video for those who haven't learned about the carbon or water cycles in other classes
- How is carbon "stored" in soils of the Arctic and Subarctic? Blog post
- What is compost? – Soils Matter, Get the Scoop! Blog post
- How can soils help with climate change? Blog post
- How does biochar work to improve, or even decontaminate, soil? Blog post
- How are biosolids used in cities? – Soils Matter, Get the Scoop! Blog post
- Microbial Metabolism in Thawing Permafrost presentation recording by University of Arizona professor Dr. Malak Tfaily (UA login required)
- The Contribution of Agriculture to Greenhouse Gas Emissions Food and Agriculture Statistics | FAO
- Engineering Side of Biomass Processing (for Biochar & Biofuel) presentation recording by New Mexico State University professor & Iowa State alumna, Dr. Catherine Brewer (UA login required)
- Prescribed Burn Crew Member (with Tyler Cross) by Half Hour Intern podcast interview about fire management, with Dr. Fidel's friend and former classmate
- It's not just Big Oil. Big Meat also spends millions to crush good climate policy. – news article
- The Compost Story (Full Video) by Kiss The Ground

- What is Soil Carbon? Blog post
- Biochar can sequester carbon in soil – so why aren't farmers using it? Recording by Dr. Fidel's mentor, Dr. Laird

## Key Takeaways

- The soil is an important carbon store
- Soil organic matter has a variety of benefits in the soil
- Management decisions impact organic matter levels and distribution

PART XI

# Case Studies

# Western Iowa Hillslope

**Amber Anderson**

Grass seed was planted equally across the area after road construction was complete, but the upper part of this slope started to establish vegetation when the lower part did not, as shown in this picture. This area is located in Western Iowa, west of the Missouri river valley in fairly sloping area.



Figure 1. Hill slope. Click to enlarge

## Review Questions

1. What soil properties might explain what is seen in this picture? What might the next management step be if you are in charge of the location?

# Corn Deficiency Symptoms

**Amber Anderson**

These photos were taken at the end of June, in a cool, wet spring. Corn on the slope shows the yellow striping, but corn at the top and bottom of the hill do not show the same pattern, in spite of being the same variety and planted on the same day. These plants were slightly smaller than the ones at the bottom of the hill. The soil core pictured on the right was pulled from the location showing the deficiency patterns:





# Tree with Chlorosis

**Amber Anderson**

This tree is located in a yard in Ames, IA. Foliage appeared normal as a smaller tree, but has become more pronounced as it has gotten larger. No treatments have been applied to either the tree or the surrounding yard.

## Review Questions

1. What soil features might be contributing to this appearance? Why would it be changing as the tree gets larger? What might you recommend for this homeowner?



# NC Iowa Crops

**Amber Anderson**

These soybeans are located in North-Central Iowa. This was a particularly dry spring, and this shoulder/backslope area showed yellowing on the leaves. Photo credits: Angie Rieck-Hinz, ISU Extension North Central.



## Review Questions

1. What soil factors could be contributing to this? What other questions do you have to figure out the cause of the solution?

# Uganda Management Challenge

**Amber Anderson**

This corn is in Kamuli District, Uganda, and would normally yield sufficient crop to be used as a staple food for the season and sold in the market, this is not used for animal feed. Fertility/tillage is not significantly different in these pictures than in years with good yields sufficient to sustain the family on the 1-2 acre plot. They can grow multiple crops per year depending upon rainfall and crops chosen, as temperatures do not fall much below 60 degrees F at any point in the year.

Recently, the little purple flowers on the right have appeared at the edge of the field, and the ears in the picture are empty. They have asked you to figure out what is going on and how might they manage this problem so they can produce enough crop.



Figure A



Figure B

## Review Questions

1. What management recommendations do you have?

2. What significant differences exist when considering management here than in the Midwest United States?

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