Introduction

The most common question gardeners ask is What is wrong with my plant?

If a plant is not growing well, there are four potential problem areas. Too little or too much light. That is an easy fix, and new gardeners soon learn to plant in the right light conditions. Watering is the next thing to consider. New gardeners struggle with knowing the correct amount of water to give a plant, but they soon learn that you water when the soil starts to dry out and that you water deep and less frequently.

Pest and disease problems are not simple to diagnose, but you can see most pests, or at least you can see their effect on the plant. Even diseases show symptoms that help you solve the problem. Prevention may not be as easy, but gardeners do learn about common pests and diseases over time.

The fourth area to consider is the soil, and even for experienced gardeners, this remains a mystery. You probably have a vague understanding about nutrients, and you have almost certainly fertilized plants before. But for most gardeners, the stuff that happens underground is a complete unknown.

Go out into your garden and have a close look at it. What do you see? The plants are obvious, especially if they are blooming, but look past the plants at the soil underneath them. You probably don't see anything except soil. You might see some mulch, or a few small stones, but except for the plant, it all looks lifeless.

Pick up a pinch of soil and hold it in the palm of your hand. You can't see them, but you are looking at billions of living organisms representing many thousands of different species. All those life-forms are trying to eke out a living. They are growing, breathing, reproducing, and the larger ones are eating smaller ones, which leads to a lot of excrement that feeds the plants.

Some are trying to attack your plants, while others are forming partnerships with them and defending them from pest organisms. Some are actually roaming the soil, collecting nutrients and delivering them back to plant roots. There are organisms in soil that you can't see, which are spoon-feeding your plants.

One of the reasons soil is so mysterious to gardeners is that our eyes can't see any of this. The number of organisms is so vast and the microbe societies are so complex, we can't get our head around it all. One of the goals of this book is to simplify the soil story and present it in such a way that you truly understand what is going on.

A few years ago, I was designing an introductory gardening course for the general public. I had a look at some large gardening books to get an idea of the main topics that should be covered. One book, of 640 pages, had 4 pages dedicated to soil. Another with over 700 pages did not have a single page on the topic. I decided to start the program by discussing soil and dedicated one-sixth of the course to it.

After 45 years of gardening experience, I realize that growing plants is very easy if you understand the soil below them. It anchors them; it feeds them; and it provides the air and water they need to survive. If you create healthy soil, you can grow anything that is suitable for your climate.

New gardeners, and even more experienced ones, tend to learn about gardening by memorizing rules. When do you transplant a peony? Should you cut back an iris? When is the best time to prune a lilac? These are all rules, and once you learn them, they are easy to follow. Move peonies in fall; cut back German bearded iris in mid to late summer; and prune lilacs after flowering. But there are thousands of different kinds of plants. You will never learn and remember all the rules for all these plants.

A much better approach is to learn the underlying science. Learn how plants grow and the role soil plays. Once you understand that, you can skip learning the rules because you don't need them, and you will be able to grow just about anything. And that is the second goal of this book: I want you to understand what is really going on in soil and how it affects plants. This book paints a simple, clear picture of the natural processes below your feet.

Once you have a really good understanding of the basics, you will be able to evaluate any gardening procedure and determine if it makes sense. For example, once you understand aggregation, you can decide for yourself if tilling is a good practice and if and when it should be used.

More importantly, you will be able to evaluate many of the fad techniques and products that are invented every year. Many of these are simply a waste of time and do not improve soil health or plant growth. You will be a more informed consumer.

What Is Soil Health?

The term is often used, but what does *soil health* really mean? Depending on your interest, it can mean many things. A climate scientist might define healthy soil as one in which the sequestered carbon is increasing. A farmer might define it as soil that produces a good yield. A microbiologist may be measuring microbe populations and diversity.

Gardeners look at plant health. If a plant is growing well, flowering profusely, and has no diseases, the soil must be healthy or at least healthy enough to grow the plant. Some grow well in nutritious soil, while others grow much better in lean sandy soil. The definition of soil health depends very much on the type of plant you are growing.

I am not going to provide a specific definition, but for the purpose of this book, healthy soil is one that grows a wide range of plants, has good aggregation, and supports a high number of microbes. Admittedly, that is a squishy definition, but it is good enough for our purposes.

Using the Book

The book has been divided into three sections, and it is important to follow them from front to back. Section 1, Understanding Soil, provides the basic science background that you need to understand your soil and the interactions between soil life and plants.

This base knowledge is then applied in section 2 that identifies soil issues and provides solutions for them. This is the hands-on section that shows you how to improve your soil.

Everybody reading this book will have different soil issues. Section 3 provides a system that will let you develop a personalized plan for improving your specific soil.

You might be tempted to jump ahead and get into the practical aspects of building healthy soil described in section 2, but it is useful to understand the underlying science. Without this base, you will find it more difficult to select the right action items and the right solutions for your garden.

Terminology

Soil scientists use well-defined terms, but these are not always used in the same way by the general public, which leads to misunderstandings. One of my challenges is to use the terms in this book such that they are useful to the gardener but still reflect the accuracy of the science. To ensure that we are all on the same page, it is critical that we must first agree on some basic definitions.

Organic

The term *organic*—which is used far too frequently to mean several different things—leads to all kinds of misunderstandings. It has become synonymous with "natural," which results in the misconception that anything organic is good for us, our garden, and the planet. The term is used extensively to describe products so that buyers think those are good choices. In the same vein, organic has also come to represent non-synthetic chemicals. In reality, many natural organic chemicals are more toxic than synthetic ones. Most drugs are synthetic and generally are safe, and yet some natural organic chemicals, such as ricin found in caster beans, are some of the most toxic compounds on Earth. Organic does not mean safe.

Organic also refers to agricultural foodstuffs that are produced "organically." This does not mean they are produced without pesticides, or chemicals; it just means that when chemicals are used, they fall under a strict set of guidelines developed by certified organic organizations. If you follow their rules, your operations are organic, even if some of the approved chemicals are synthetic or toxic. The rules become paramount, and safety is secondary.

To a chemist, the word *organic* means something completely different. An organic chemical is any chemical that contains carbon, with the exception of some salts. All sugars, carbohydrates, and proteins contain carbon and are organic, even if they are human-made. Anything that does not contain carbon, including most plant nutrients, is inorganic. By this definition, most synthetic pesticides are organic.

This book will use the chemist's definition of organic and the term *certified organic* to refer to organic agriculture.

The term *organic soil* is used differently by gardeners and soil scientists. For gardeners, it refers to soil that has been treated organically following certain organic certification rules. To soil scientists, it is soil that was created by the layering of plant material instead of the degradation of rocks. It usually contains more than 20% organic matter, and peat bogs and marshes are good examples of this kind of soil. This book uses the latter definition.

Organic Matter

The term *organic matter* is used in a very general sense to refer to any dead flora, fauna, or microbe. This could be recent dead material, such as wood chips and manure, or a highly decomposed form, such as compost or humus.

Fertilizer

The term *fertilizer* can have many definitions. Gardeners often think that the term refers only to synthetic chemical fertilizers, but that is not a correct usage since there are many organic fertilizers that are not synthetic.

Many jurisdictions use a legal definition for fertilizer that requires that the product contain nitrogen, phosphorus, and potassium, and that the amounts of these nutrients are labeled on the package as the NPK value. By this definition, something like Epsom salts would not be a fertilizer even though it provides plants with magnesium. Its NPK value would be 0-0-0, which is not a fertilizer.

In a more general approach, I will use the term *fertilizer* to describe any material that is added to soil with the primary purpose of supplying at least one plant nutrient. I will also use the term *synthetic fertilizer* to refer to human-made chemical products and *organic fertilizer* for natural products.

Fertilizer vs Soil Amendment

A soil amendment is something that is added to soil with the primary purpose to change its physical properties, such as water retention, permeability, drainage, and structure, as well as changes to pH. Lime, for example, is usually applied to change pH, but it also adds some nutrients. Since the primary purpose is to modify the soil, it is a soil amendment, not a fertilizer.

In some cases, the differentiation between *fertilizer* and *amendment* is not clear-cut. Compost is used by most people to add nutrients for plants—as fertilizer—but it also improves the physical properties of soil, so it is also an amendment. Sulfur can be an important component in fertilizer, and it is used to change pH.

Another term in common use is *soil conditioner*. Some try to differentiate between amendment and conditioner, but in this book, they are one and the same and will be called a soil amendment. Many amendments can simply be layered on top of soil, instead of incorporating them into the soil, in which case they are referred to as both amendment and mulch.

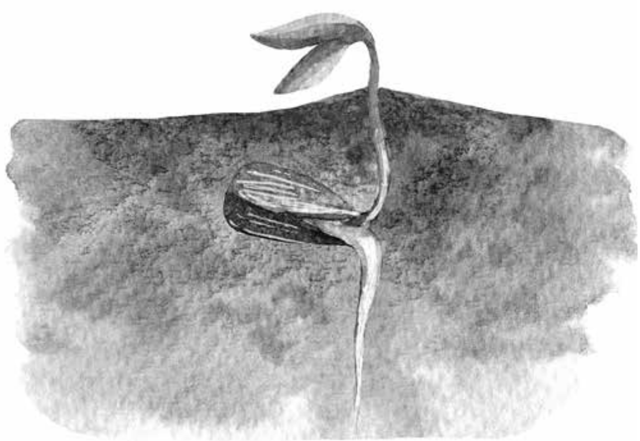
Microbes

A large part of this book is focused on the life forms in or on soil. These organisms are classified as flora (plants) and fauna (animals), and these terms work well for the larger ones like mice, earthworms, and perennials, but as their sizes decrease, the difference between plant and animal gets muddy. Many small organisms have some characteristics of both. Most bacteria don't have chlorophyll, so they can't make food from sunlight like plants can, but they don't have many animal characteristics either. And then there are the cyanobacteria that do photosynthesize and the fungi that are more plant-like but don't photosynthesize.

The difference between these organisms is a fascinating subject, but for a gardener, we can keep things simple. I'll use the general terms *microbe* or *microorganism* to refer to this varied group of small organisms.

SECTION 1

Understanding Soil



CHAPTER 1

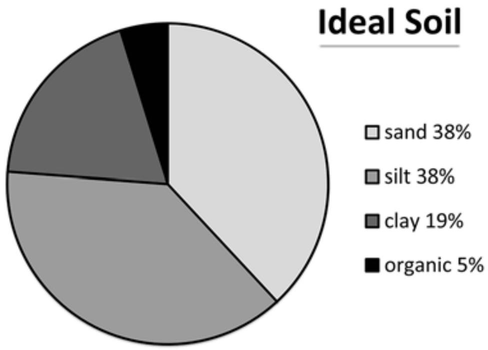
Soil Basics

Nobody has a problem recognizing soil, but it is actually difficult to define. Over the years, its definition has also changed, with the latest one being developed by the Soil Science Academy of America in 2016: "Soil is the top layer of the Earth's surface that generally consists of loose rock and mineral particles mixed with dead organic matter."

It is important to note that this definition does not include the many different organisms that live in soil. This will probably come as a surprise to you since so much is written about the *living soil* and the need to *feed soil*, terms that have led to various misunderstandings about soil.

People make the claim that "soil is alive," and then go on to describe how to feed the soil in order to maintain a balanced health, describing various food that soil wants to eat. The whole idea that soil is a living organism that requires similar attention to animals is completely false and leads to many poor recommendations for managing soil.

Soil is not alive. It does not need to eat or breathe. Soil can be improved to make it better for growing plants, but this is not a health issue in the way animals are either healthy or sick. When people talk about a living soil, they are actually referring to a soil ecosystem that consists of soil and all of the living organisms in and on it. This ecosystem does have life in it, and it supports life, but even it is not alive.



Components of ideal soil.

Components of Soil

If we exclude the small and large rocks, soil has four components: sand, silt, clay, and dead organic matter (OM). The ideal soil contains these in the ratios shown in the diagram. What is a surprise to many is that, by weight, the organic matter makes up only 5%. On a volume basis, it is about 10%. Although OM is only 5%, it is extremely important for providing soil its physical and chemical characteristics.

This concept of ideal soil is a bit misleading since almost nobody has soil with these ratios. You might think it is your job to convert your soil to these ideal ratios, but that is neither practical nor necessary. Consider that almost none of the soil on Earth is ideal, and much of it grows plants just fine. Plants are very adaptable and will grow in most soil.

Changing the amounts of sand, silt, and clay to any great degree is almost impossible because they make up such a large percent of the soil, but you can change the OM level, and since it is a small part of soil, a change of even a fraction of 1% can have a significant effect. The more your soil ratios deviate from ideal, the more issues you will have with your soil.

Origin of Soil

To better understand soil, it is instructive to understand its genesis. Soil starts as large rock formations. Over time these are broken up into smaller and smaller pieces through the action of physical, chemical, and biological weathering. Wind and rain slowly break small pieces off larger ones. Water gathers in cracks, and when it freezes, the rock splits apart. Falling rain picks up CO_2 from the air, resulting in acidic water with a pH of about 5.5, which slowly dissolves some types of rock like limestone. Moss and lichen grow on rocks, and the chemicals they produce through roots slowly dissolve the rock.

It is a very slow process, but one that is continuously taking place. Sand, silt, and clay are just rocks of varying sizes. Eventually, the rock is broken down even more, into its basic elements, which are the nutrients plants use to grow.

As the particles get smaller, it becomes easier for nature to move them around. Rivers and glaciers take rock from one location and move it many miles away. Wind and rain also play a big role in moving soil, especially on sloped ground. The soil at the top of a hill can be quite different from the soil at the bottom. It is estimated that 95% of the Earth's soil has been moved from the area in which it was created.

The soil in your area is the sum of all of these actions. In theory, your soil is made from the bedrock that exists where you live, but it could have moved there from many miles away. Nevertheless, it is still a product of the parent rock that made it.

Granite, sandstone, and shale result in acidic soil because those rocks are acidic. Limestone and basalt, which contain a lot of calcium and magnesium, will result in alkaline soil.

Soil Particles

Soil consists of varying sizes of small rocks, and in order to quantitate them, scientists use the terms sand, silt, and clay. Large pieces, above 2 mm, are called rocks. Sand refers to pieces between 2 mm and 0.5 mm. Silt varies from 0.5 mm to 0.002 mm, and clay is smaller than that. To put those numbers in perspective, if a piece of sand was the size of this page, silt would have the width of one letter and a piece of clay would be smaller than the period that ends this sentence.

Physical Characteristics of Sand, Silt, and Clay.

Property	Sand	Silt	Clay
Particle size (mm)	2.0–0.05	0.05–0.002	<0.002
Visible to naked eye	Yes	No	No
Cohesion (attraction to each other)	Low	Moderate	High
Ability to hold water	Low	Moderate	High
Rate of water infiltration	Rapid	Slow	Slow
Degree of aeration	Good	Moderate	Low
Resistance to pH change	Low	Moderate	High
Ability to hold nutrients	Low	Low	High
Compactability	Low	Moderate	High

Sand

Sand is large enough to be seen with the naked eye, and if you rub some soil between your fingers, you can even feel its gritty nature. Sand particles can exist in many shapes, but you can think of them as being round.

The physical property of sand is a function of its size and shape. It does not pack very well, and it has a lot of air space between the particles. When you walk on sand, it tends to move out of the way rather than compact. Sandy soil is easy to dig and is usually described as light and crumbly.

From a chemical perspective, the surface of sand is very stable. It does not react with most chemicals, and water doesn't stick to it very well, which is one of the reasons it drains quickly.

Silt

Silt is too small to be seen by eye, and if you rub it between your fingers, it feels very smooth, like talcum powder. You can think of silt as being small sand particles. They are chemically stable, but due to the smaller size and smaller air spaces between them, water does not drain as quickly as in sand. Silt also compacts more easily than sand.

The properties of silt tend to be halfway between those of sand and clay. Like sand, its particles do not stick to one another, and they don't hold water tightly.

Clay

Clay consists of the very smallest particles, including anything below 0.002 mm. They are so small they can't even be seen with a light microscope.

Whereas sand and silt can be thought of as round particles, clay consists of flat thin plates that pack very close together. Think of a loaf of sliced bread with each slice being a clay particle. These particles are highly charged, which makes them react with themselves and other chemicals. Water and nutrients stick to them.

When you handle clay, it sticks together, and you can easily role it into a ball that retains its shape. This makes it fun to play in but not so great when you have to dig in it. A shovel of clay soil tends to retain its shape, forming clods of soil.

As a result of its size and chemical properties, clay behaves quite differently from sand and silt. It holds water very tightly, and even though the spaces between the particles are small, the total volume of space is large, allowing clay to hold significant amounts of water. This, along with its charged nature, means that clay takes a long time to drain.

Clay also expands when it gets wet and shrinks when it dries. You can see this in the form of cracks on the surface of the soil. Clay is easily compressed, especially when it's wet. Walking on clay squishes the slices of bread even closer together, and once compressed, it is difficult to decompress them by physical means.

Unlike sand and silt, which result from rocks breaking up into smaller and smaller particles, clay is formed when very small minerals stick together to form larger particles. Since clay is created, it has the properties of the parent minerals, and there are many different kinds of clay. As clay is formed, it also incorporates particles of organic matter and plant nutrients.

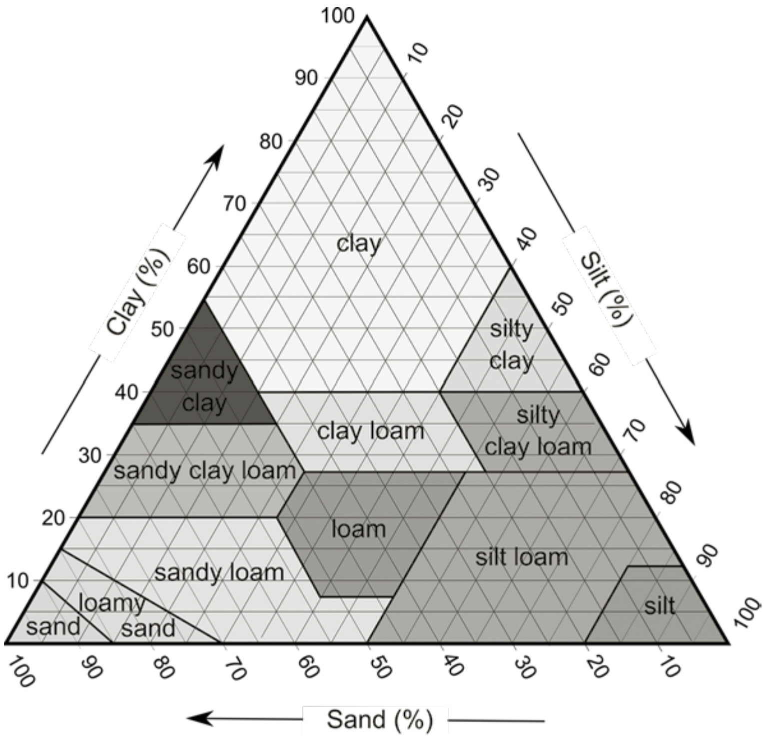
Soil Texture

We have talked about sand, silt, and clay as if they occur as isolated soils. This can happen in special situations, but it is much more likely that they occur together. Such soil will have properties somewhere between the extremes.

Scientists use the term *soil texture* to describe the ratio of sand, silt, and clay in a given sample, as illustrated in the soil texture diagram.

Ideal soil, which has 40% sand, 40% silt, and 20% clay, is referred to as loam. If the soil contains a larger amount of clay, it is called clay loam. A very sandy soil with some clay and silt is called sandy loam.

These soil designations are helpful when referring to a particular sample, or when you have a discussion with someone else with different soil because a sandy loam will function differently than a clay loam. Knowing your texture, which is easily determined by the soil texture test, will help you understand the physical and chemical properties of your soil.



Soil texture triangle.
Credit: https://commons.wikimedia.org/wiki/File:USDA_Soil_Texture.svg

Importance of Particle Size

Particle size affects two important soil characteristics: the surface area and the amount of pore space (both number and size of spaces between particles). Large particles have a relatively small surface area with few large pores. Small particles have a large surface area and many small pores. These properties affect the way water travels through the soil, and it impacts where and how roots grow.

After a rain, most of the pore spaces are full of water, but that soon runs away. What is left is a lot of soil particles that are each covered in a thin film of water that lasts for days, and even weeks. It is this thin layer of water that plant roots use to get their moisture.

Sand has a relatively small surface area, compared to clay. To put this into perspective, a handful of sand has a surface area equivalent to the top of a table, whereas a handful of clay has a surface area equal to a football field. For this reason, clay holds much more water and stays wet much longer, making it easy for roots to get water for a longer time.

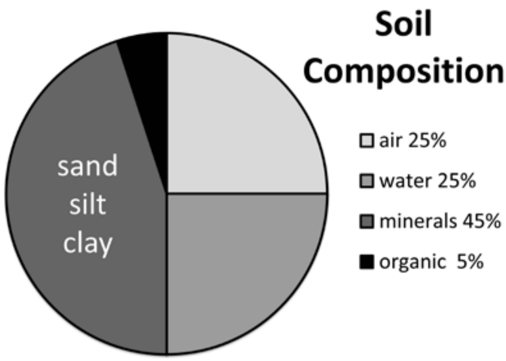
Nutrients also stick to the surface of particles, so a larger surface area also means that there are more nutrients available to plants. This is one reason why clay is very nutritious.

Air and Water

The term *soil solution* is used to describe the water that is attached to the surface of soil particles.

Air and water are critical for proper plant growth. What most people don't realize is the large amount of both in soil. The actual amount depends on several factors, such as its texture, the amount of organic material, and the degree of compaction, but ideal soil contains about 25% air and 25% water.

Immediately after a heavy rain, much of the air is forced out and replaced with water. Gravity, evaporation, and plants will reduce the level of water, which is then replaced with air. Perfectly dry soil will have no water and 50% air. Such dry soil is rare and is mostly found in laboratories. Most soil holds some water, even if plants are no longer able to get any of it.



Composition of ideal soil.

Evaporation is the process by which liquid water turns into water vapor and escapes into the air. This happens right at the surface of the soil, which is why the top layer of soil can be quite dry while the soil is still quite wet a few inches down. As evaporation takes place, more water will be drawn to the surface by capillary action. This process slowly dries out the soil.

Gravity is also at work, pulling water down deeper into the soil. Eventually it is down far enough to enter reservoirs deep in the ground, or, depending on topography, it might flow into a river or lake.

Plant roots are constantly absorbing water and transferring it to their leaves, where much of it evaporates through leaf openings called *stomata*. Some is also used in chemical processes like photosynthesis. This effect of plants is significant. A large tree can remove up to 100 gallons (400 liters) of water a day and discharge this into the air as water vapor.

As water leaves the soil, the pore spaces are filled with air. As soil dries, more and more air enters the soil. This cycle is repeated next time it rains or you irrigate. It is important to understand that there is always some air remaining in soil, and this is critical for plant health since roots need oxygen.

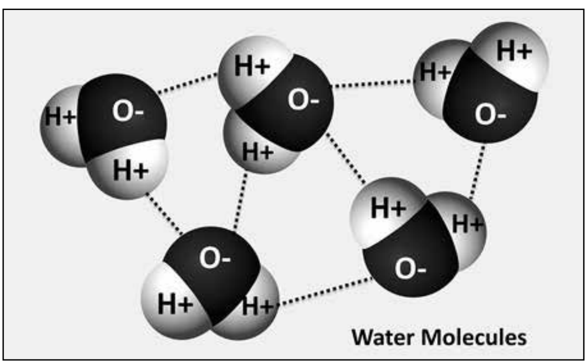
Most people have heard about photosynthesis, a process in which plants absorb carbon dioxide (CO_2) from the air, produce sugars using sunlight, and then give off oxygen (O_2). This is the opposite of what animals do. They absorb O_2 and give off CO_2 in a process called respiration.

What you may not realize is that plants also respire, absorbing O_2 and giving off CO_2.This happens not only at night but also during the day and for the same reason animals do it. The process allows plants to convert sugars into energy, which they need for growth. This takes place in all their parts, but a lot of it happens in the roots; they need to be able to absorb oxygen from the soil, or they die.

This explains why many plants can't grow in areas that are constantly wet. This kind of soil does not provide enough oxygen for roots. It also explains why plants die if you water too much and why some plants just don't grow well in clay soil that does not hold enough air.

Chemical Nature of Water

The molecular formula for water is H_2O: two hydrogen atoms for every one of oxygen. But the three-dimensional structure of water is much more interesting than this: it looks like a wide V, with the oxygen at one end and the two hydrogen atoms at the other. Because of this structure, one end of the molecule has a positive charge and the other has a negative charge. You can think of water molecules as being small magnets, with one end being attracted to the other. This sticky nature of water, called cohesion, plays a key role in understanding how water and nutrients move through soil.



Water molecules react like little magnets.

Movement of Water Through Soil

It has just rained, and the top layer of the soil is saturated with water. Why does this water not run away? Why does gravity not pull it straight down?

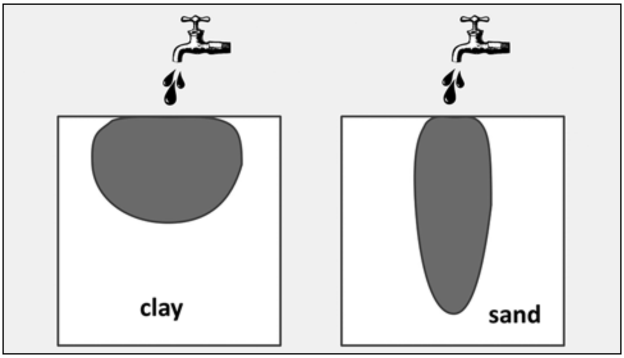
The answer lies in the cohesive properties of water. The electrical charges on the water molecules are much stronger than the force of gravity. In effect, the water molecules hold on to each other and to soil particles so tightly that gravity can't pull them down very far.

Remember the evaporating water at the surface of the soil? As the surface water molecules evaporate, they pull the next lower molecules higher because of cohesion. And since each of these are connected to even more molecules lower down, many are pulled up, preventing gravity from pulling the water lower.

There is also another force at play. Clay and organic matter also have negative charges. The positive ends of water molecules stick to the negative charges on clay and OM. These in turn hold onto other water molecules, making it even harder for gravity to pull the water down.

It is interesting to watch what happens when water is dropped onto soil: it does not run straight down as you would expect. The water does moves down, but at the same time, it moves sideways in all directions due to the interplay of charges on clay, OM, and water.

Sand particles have large pore spaces and almost no charge. Water will form a very thin film around each sand kernel, but since sand is not charged, this film is not held very strong.



Movement of water in clay and sand.

Water can hold onto itself, but there is a limit in its ability to do this. The pore spaces between particles of sand are just too large for water to fill the space and stay there. Gravity takes over and pulls water out of these spaces fairly quickly. This explains why sand drains so fast. When water is dripped onto sand, most of it runs down, but a bit also runs sideways due to the cohesive nature of water.

Clay soil behaves quite differently. Clay particles are negatively charged, and the pore spaces are very small. Water sticks to clay very tightly and completely fills the pore spaces. Gravity is no match for these forces, and as a result, water dripping onto clay moves sideways much more than in sand. These properties of clay also reduce the rate of evaporation.

So far, we have been discussing pure sand and clay soil, but real soil also contains organic matter that also has negative charges, just like clay. Water also sticks to OM very tightly. As an example, silt loam with 4% OM has twice as much water available as the same soil with 1% OM, illustrating the important of organic matter for plants.

Over time, evaporation, gravity, and plants do reduce the level of water in soil. The large pores are emptied first, then the medium-sized pores, and finally the very small pores. Plant roots are relatively large and can grow only in the large and medium pores. They just don't fit in the small pores.

What happens when a plant root grows into a pore space? The surface of the root comes in contact with the water layer around the soil, and it is able to absorb the water. Remember those little water magnets and how they reacted with evaporation; the same happens here. As a water molecule is pulled into the root, it pulls more water into the space that was vacated. This results in a constant flow of water, from areas away from the root toward the root.

It is the cohesive nature of water that allows roots to pull water from small pores, even though they are too big to fit into the spaces. This all works great, but in time, the water layer gets thinner and thinner because there is just less water in the soil. At some point, the flow of water stops, and roots just can't get enough water.

Plants grow new roots where they are able to get water, nutrients, and oxygen. As the top of the soil dries, new growth happens deeper in the soil where they can still access water. Watering deeply and less frequently results in the development of deep roots that allow the plants to survive dry periods.

Aggregation and Soil Structure

So far we have looked at soil on a microscopic level, but soil is much more than that. If you go into an established woodlot and get your hands in the soil, you will notice that it does not really feel like a bunch of sand, silt, and clay. It consists of large crumbly pieces that are dark in color. It is very airy with lots of pore spaces of all different sizes.

What you are looking at is the macro structure of good soil. The smaller pieces of sand, silt, and clay have been mixed with OM to form larger structures called *aggregates*. Aggregation is not well understood by gardeners, but it is a very critical part of good soil. When soil has it, you will grow lots of plants. When aggregation is lacking, the soil performs poorly. Creating good soil is all about improving aggregation.

The key to aggregation is a special sauce that goes by various names, including binding agents, mucus, organic binders, and organic cement. This binding agent acts like glue to stick the sand, silt, clay, and organic matter together into large soil particles, which soil scientists call *peds*.

The binding agent consists of many different kinds of chemicals produced by living organisms. You can think of them as life juices. Plants, bacteria, fungi, earthworms, and small insects all excrete juices, and some of the chemicals work great as a glue.

Clay, iron oxide, and OM also act as cement in forming aggregates, but microorganisms provide the best binding agents. Sodium reverses the aggregation process and can even prevent it from forming in the first place. This is one reason that irrigation with sea water is a problem.

Aggregation is a two-step process. First, binding agents from various microbes help stick very small particles together to form microaggregates. Then the microaggregates are stuck together into macroaggregates by the mycelium of fungi and hyphae of actinomycetes. There is a direct relationship between size of aggregates and the fungal biomass. The cultivation of soil breaks down fungi mycelium, resulting in a marked decrease in macroaggregation.

Why are aggregates so significant to gardeners? Aggregates indicate a healthy soil system since they form only if the amount of dead organic matter or living microbes is high enough, both being critical for plant growth. More importantly, large pore spaces that are a perfect size for roots are created between the aggregates. The larger pore spaces also make it easier for water and air to move through the soil, increasing drainage and providing oxygen for plant roots.

The structure of aggregates is fairly loose and contains many small pores that hold a lot of water. Microbes also use these smaller channels to hide from larger organisms.

Earlier in this section, I described the soil from a virgin forest. I strongly suggest you visit one and play in the soil. You will be able to both see and feel the aggregates. Look at the various sizes of particles. Feel how crumbly they are, and how easily you can move your

Soil Test: Degree of Aggregation

Remove surface debris from the soil. Try to insert your fingers into the soil. If this can be done easily, you have either a very sandy soil or a high level of aggregation.

Dig up a shovelful of fairly dry soil. Can you see large crumbly pieces, or does it look like sand and silt? Compare the look to the soil in an established wooded area. If you gently squeeze one of the larger pieces, does it fall apart easily? You want to see large pieces of aggregation that can be easily broken apart into smaller pieces that are still larger than sand.

Sandy soil with no aggregation falls apart into sand, and the particles are clearly not stuck together. Clay soil without aggregation forms clods that are hard to break apart, and you can't see any mid-sized particles.

fingers through them. The long-term goal for your garden is to produce the same kind of soil.

Aggregation is a continuous process that is either improving or getting worse. The natural binding agents slowly decompose and need to be continuously replaced by microbe activity. Provided the rate of activity is high enough, aggregation continues to get better.

Soil could have significant aggregation, but the aggregates might not be very stable, which means they easily break apart at the slightest change in soil condition. Very stable aggregates can take some destructive forces and remain intact. The aggregate stability test, also called Archuleta slake test, can be used to measure quality.

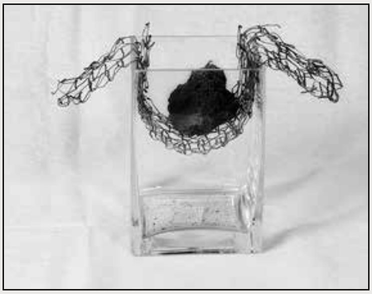
Soil Test: Aggregate Stability

Dig up a shovelful of fairly dry soil. Gently break it apart into large pieces, and find a chunk about the size of a golf ball. Set it on some paper and let it air-dry for at least 48 hours so the test can be done on dry soil.

Prepare a clear glass jar that is at least 5 inches high. Cut a piece of wire mesh with ¼-inch holes, and use it to form a basket that will sit on top of the jar, as show in the picture. Fill the jar with water so the water is several inches above the basket.

Gently place the chunk of soil into the basket and wait. Water will rush into the pores, causing significant shear forces. A stable aggregate will remain intact. A poorly formed aggregate will fall apart.

Wait for 1 minute. If the aggregate has mostly fallen apart, score it a 3 for poor stability. If it breaks down in 1 to 5 minutes, score it a 2. If it is still mostly intact after 5 minutes, it is very stable, and you can score it a 1.



Jar and bracket used in aggregate stability test.

Soil pH

Soil pH can have a significant effect on plant growth, which is why so much has been written about it.

The pH scale measures the number of hydrogen ions in a liquid, given as a number between 0 and 14, with a pH of 7 being neutral. Anything above 7 is alkaline (low level of hydrogen ions), and below 7 is acidic (high level of hydrogen ions). Most plants grow best at a pH between 5.5 and 7.0, but some plants prefer values above or below this. Soil pH ranges from 3.5 to 10.5, but these are extremes; most are between 5 and 8.5.

This is fairly common knowledge, but what most people don't know is that pH is measured on a logarithmic scale. (Do you remember high school math?) This means that a pH of 8 is 10 times more alkaline than a pH of 7; a pH change of 1 unit is actually an acidity change of 10 units. A change of 2 numbers, for example 5 to 7, is a change of 100, which is a significant change.

The pH of your soil depends very much on the rock that formed it. Granite, sandstone, and shale are acidic rocks and produce acidic soil. Limestone and basalt are alkaline rocks and produce alkaline soil. They continue to decompose, and as long as some rocks remain in your soil, it will be difficult to change the pH.

Calcareous soils are a bit different. They have an underlying layer of chalk or limestone rock and contain a high level of calcium carbonate ($CaCO_3$). Organic soil is also different because it was created by the layering of plant material instead of the degradation of rocks. It usually contains more than 20% organic matter and is found in peat bogs and marshes.

The pH of local soil is also affected by rain in two ways. As it falls through the sky picking up CO_2, it forms carbonic acid, and by the time this hits the ground, the pH of the rain is about 5.5. If it also picks up pollutants as it drops, it can be even more acidic.

A high rainfall, as exists in the eastern US, keeps soil acidic by washing minerals (cations) deeper into the soil, which increases the relative number of hydrogen ions near the surface. In dry regions like the western US, a lack of rain results in water moving from lower levels up to the surface due to evaporation, carrying up minerals like calcium and sodium, resulting in alkaline conditions.

Other natural processes can acidify soil:

- Respiration by soil roots and soil organisms produces CO_2, which is acidic.
- Decay of organic matter produces organic acids.
- Plant growth absorbs minerals from the soil leaving behind hydrogen ions.

The pH of soil can also be changed manually:

- Sulfur decreases pH.
- Lime increases pH.
- Fertilizers can increase or decrease pH.
- Compost and manure can change pH.

The reality is that changing soil pH long-term is much more difficult than claimed in books and on the internet. In most cases, it quickly reverts back to its original pH.

You have probably seen suggestions that the ideal pH range for plants is 6 to 7. This is true for mineral soils (made from rock), but for organic soils (peat and marsh bogs), a better range is 5.5 to 6.

Soil Myth: Soil pH

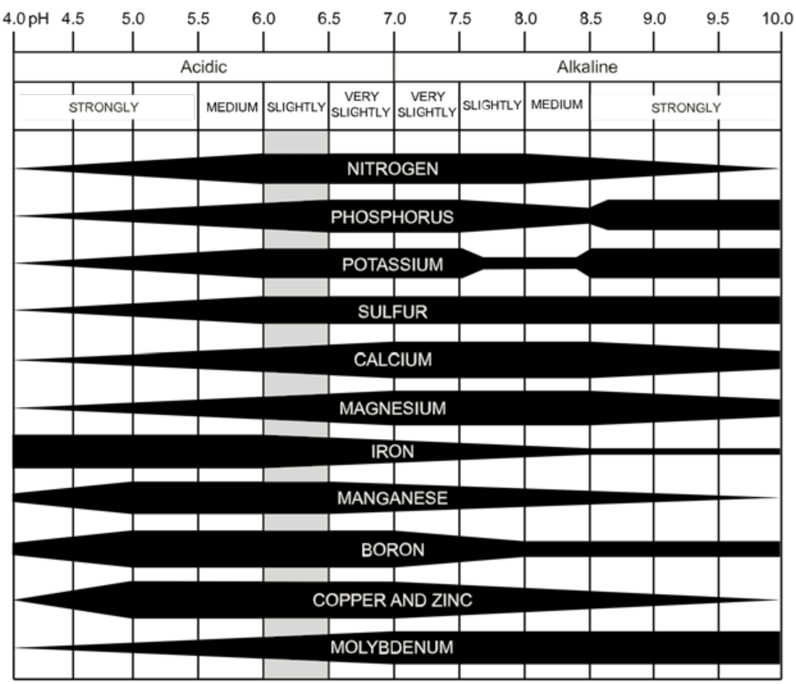
People talk about "soil pH," but what they are actually referring to is the pH of the water surrounding the soil particles—the soil solution. It is also an average of the total soil area. Specific locations within the soil can be quite different. A spot with organic matter and lots of bacterial activity will have a different pH from an inch away where there is less organic matter. The pH right next to a clay particle can be as much as 1 pH unit different from the water that bathes the clay.

The rhizosphere, the area right next to a plant root, can have a very different pH from the soil solution pH.

pH and Nutrient Availability

Given all of the talk about pH and plant growth, you would think that pH is essential to plant growth, but in reality plants are not directly affected by the level of hydrogen ions. The issue with pH is that it affects the nutrient levels in the soil solution and therefore influences plant growth. The chemistry gets a bit complicated, so I'll just provide a few examples to illustrate this.

Imagine a soil that has pH 7 and plenty of nutrients for plants. If we add some hydrogen ions, the pH will become more acidic. At this lower pH, phosphorus reacts with aluminum and precipitates, reducing the number of both ions in the soil solution. Plants now can't get enough of either one to grow properly. There is still lots of phosphorus and aluminum in the soil, but it is now in a form that plants can't use.



pH affects nutrient availability. Credit: https://commons.wikimedia.org/wiki/File:Soil_pH_effect_on_nutrient_availability.svg

If, however, we make our imaginary soil alkaline, calcium reacts with iron and reduces the amount of iron ions in the soil solution. Plants now show interveinal chlorosis due to a lack of available iron. Iron is essential for making chlorophyll, the green part of leaves, and when plants can't get enough, they develop a yellow coloration in the spaces between the veins. The problem is not a lack of iron but a lack of available iron.

Most plant nutrients are affected by pH. In general, nutrients are more available at a neutral pH and become less available at extreme pH values. The chart shows how the availability of various nutrients changes with varying pH. Keep in mind that it shows relative amounts and can't be used to calculate the amounts available at any given pH.

pH and Toxicity

Plants need certain nutrients, but these same nutrients can become toxic if they exist in concentrations that are too high. At a low pH, aluminum and manganese can reach toxic levels.

Aluminum ions are found in the soil solution and inside clay particles, but the amount in the soil solution at higher pH is normally low. As pH becomes more acidic, the aluminum inside the clay particles is released and enters the surrounding water, dramatically increasing the concentration. At some point, aluminum becomes toxic and inhibits root growth. Aluminum toxicity is not usually a problem in mineral soil that has a low level of clay, or in organic soil.

Aluminum sulfate is a commonly recommended fertilizer, but due to possible toxicity, it should not be used on clay soils.

pH and Soil Organisms

Organisms living in soil are also affected by pH, and most grow best in neutral soil. Bacteria and actinomycetes prefer a slightly alkaline pH, and fungi prefer it a bit more acidic. Earthworms and larger organisms need a pH above 5 and do best near 7.

Specialty microbes can be found at almost any pH. Bacteria exist at both pH 1 and pH 11.