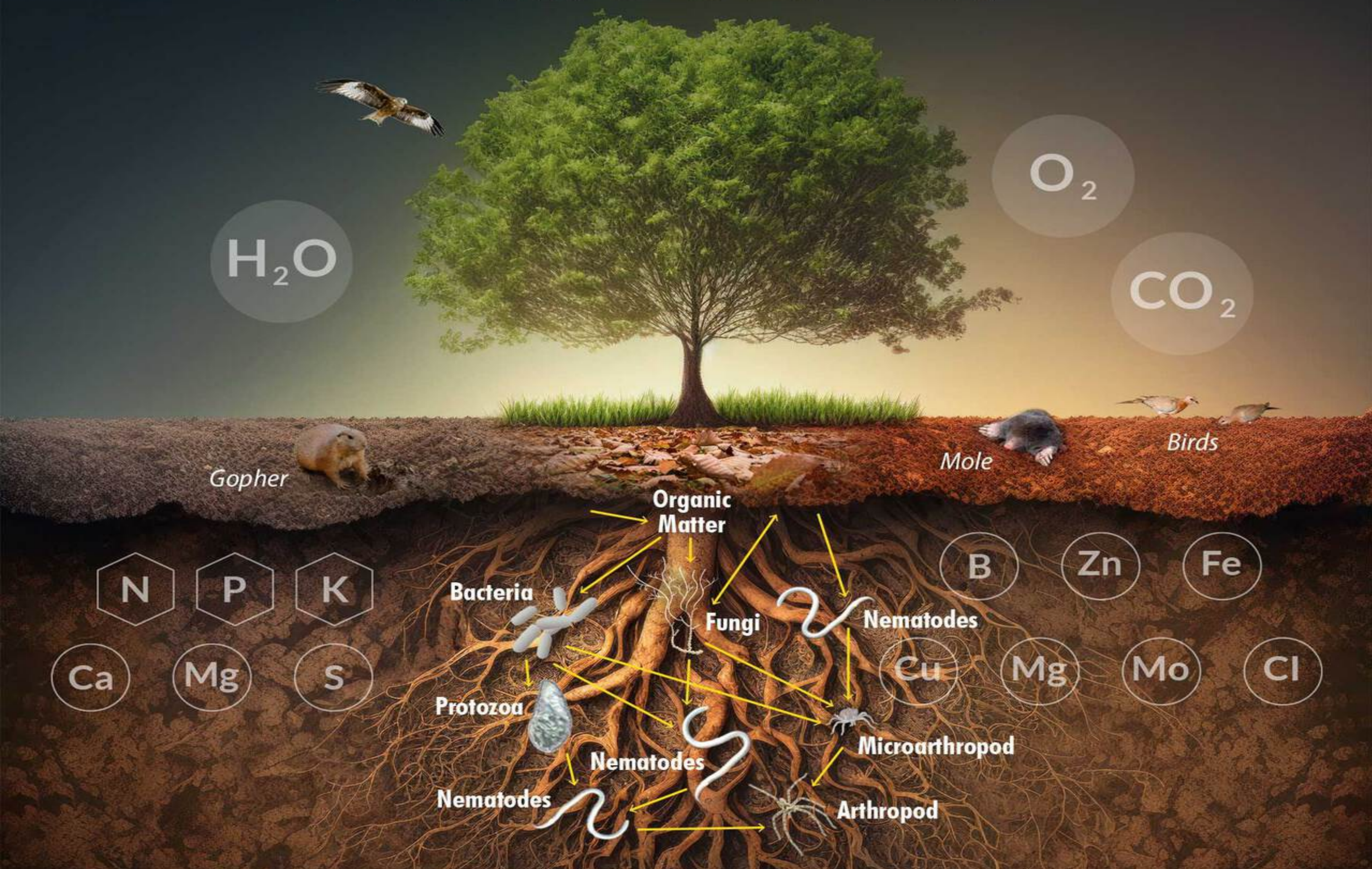
SOIL SCIENCE

FOR REGENERATIVE AGRICULTURE



A COMPREHENSIVE GUIDE TO LIVING SOIL, NO-TILL GARDENING, COMPOSTING, AND NATURAL FARMING

COMPLETE WITH A STEP-BY-STEP ACTION PLAN TO QUICKLY GROW SOIL

AMÉLIE DES PLANTES

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ECOLOGICAL
FOOD FOREST

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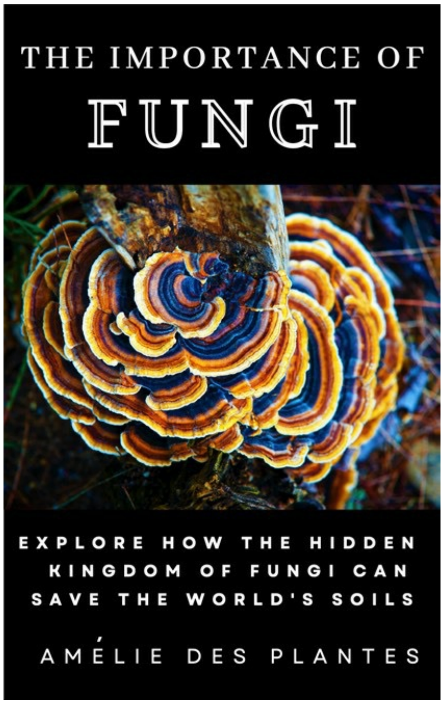

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SCAN ME

1

INTRODUCTION

"*The nation that destroys its soil destroys itself.*" –Franklin D. Roosevelt

Changing face of global threats including environmental degradation, mass consumption and disease emergence has put human health and climate change issues at the forefront. The pandemic for one has made people a lot more concerned about their health while drastic climate changes and climate disasters have stirred political debates. There is a greater sense of realization regarding the conservation of resources and remediation of pollution, yet everyone is ignoring the root problem; the destruction of natural resources and ecosystems.

Did you know that 95% of all our food is grown in the uppermost layer of the soil? This layer, topsoil, is critical when it comes to growing crops because it contains everything that a plant needs. However, this layer is eroding at a rapid pace, and we could run out of it in about 60 years if no remedial measures are taken to restore and replenish it (Cosier, 2019).

The rampant use of chemical fertilizers has severely altered the soil's nutrient balance and the indigenous microbial systems. Besides that, excessive tilling and a lack of cover crops have contributed to soil erosion, the reduction of soil water retention abilities, and the loss of essential soil nutrients. All of these effects have resulted in an overall reduction in soil fertility, quality, and quantity, resulting in the compromised safety of food crops. Excessive application of fertilizers has not only affected the soil composition but has undermined the safety of our food. Research shows that our food web is contaminated with several chemicals from these fertilizers. These chemicals are also known to enter bodies of water where they cause damage to aquatic life. That said, the exact amount of the pollutants that enter the soil is unknown, and so is the exact scale of damages that these pollutants are causing for both humans and animals.

Damage to the soil structure and chemistry also means that its water filtration and retention capacity is compromised. The natural structure of soil performs physical and biochemical purification of water until it reaches the bottom. But with eroded soil layers and disturbed soil microbiota, the efficiency of these functions has been jeopardized. Soil is also the second largest reservoir of active carbon after oceans, which are the largest carbon reservoir (and their ecosystems preservation requires an entire book of its own). Both of these reservoirs have great potential to neutralize global warming issues. Unfortunately, the industrial waste, urban waste, and unsustainable agricultural and farming practices are severely damaging their carbon-storing capacity.

The loss of soil not only means environmental and food security issues, but it also means the loss of habitats to several animal and plant species. According to the “species-area relationship,” this kind of destruction where natural habitats are damaged or disturbed is viewed as an extinction of the species. The numbers regarding species extinction are horrifying. It has been reported that we have a current extinction rate of 150 species per day, which means that we could be in the midst of the sixth mass extinction (Pearce, 2015; United Nations Environment Programme, 2007) (Secretariat of the Convention on Biological Diversity Message from Mr. Ahmed Djoghlaf, Executive Secretary, on the Occasion of the International Day for Biological Diversity, 2007). Soil is also an excellent water sponge. This sponge filters rainwater and maintains high groundwater levels, and human activities are meddling with these processes. Changing soil composition allows hazardous wastes and chemicals to easily pollute the groundwater reservoirs. Furthermore, the water retention capacity lowers, which means that more water is being lost as runoff. This runoff water is contributing to soil erosion and the sedimentation of water bodies.

We are under the impression that simply upgrading our hygiene standards will help us have a healthy life when in fact that is not completely true; the health of the soil is the greatest determinant of our health. We cannot dream of having healthy bodies when we are damaging our soils.

The latest research data has revealed that the microbiome of our gut and that of the soil is highly similar (Hirt, 2020). This similarity is not surprising. The plant components that we consume (leaves, fruits, and roots) contain microbes of soil and the consumption of these components transfers these microbes to our gut. This means that any changes in the plant microbiome directly affect our gut microbiome. In short, all the chemical fertilizers and pollutants that harm the soil's microbiome are injurious to our health. Due to this reason, excessive use of fertilizer has been linked to various kinds of cancers, diabetes, thyroid problems, and fetal developmental defects.

All of the major problems that humankind face are somehow related to the soil, and living, flourishing soil is the key to solving all of them. These issues have not been present from the emergence of mankind; human activities have slowly exacerbated these issues. In turn, we have been relying on governmental and non-governmental organizations to tackle them. In reality, each of us needs to play an active role in preserving the soil and ecosystems. By giving our soil a chance to thrive, we can improve our ecosystem and our health, thus making a difference for ourselves and future generations.

I have been practicing permaculture and organic farming for decades now, and I want to share my knowledge and experience to help you play an active role in remediating soil, growing your food, and preserving the ecosystem. I want to help you deal with your eco-anxiety. You can’t afford to sit around and wait for someone to tend to the soil. It is your responsibility to live sustainably and to return to the soil what you have taken from it. Several climate activists like Jane Fonda and Leonardo DiCaprio are playing active roles in ecosystem preservation, but your role is just as important.

Besides the benefits listed above, connecting with soil will help you relieve stress. You’ve probably heard how gardeners and farming enthusiasts say that spending time in the dirt takes away their anxiety and depression—well, compelling scientific evidence makes this a difficult fact to ignore (Lowry et al., 2007). Some of the microbes found in dirt mimic the positive outcomes of pharmaceutical antidepressants. Soil is your natural antidepressant without the potential dependency!

But before you take a spade and start working with soil, I want you to dig into some of the basic information about soil science including soil composition, biogeographic cycles that soil is a big part of and the methods through which soil fertility can be maintained. Just like any other living thing, the soil needs replenishments and care to stay in its optimum condition. I will teach you to do that in an easy-to-do way. As a permaculturist, I have had my fair share of successes and failures and have learned lots from these experiences. I will be sharing these experiences with you to help you kickstart your journey to living soil, no-till gardening, and sustainable farming.

PART I

1

REGENERATIVE AGRICULTURE AND WHAT IS LIVING SOIL?

Before we delve deeper into the details of soil science, let's first look at some basic questions about soil. Have you ever wondered what soil is? Is it living or dead? Which state of matter does soil belong to? What is its chemical and biological composition? Was the soil exactly like this a million years ago or has it changed over time? Let us look at the answers to all these questions.

Approximately 75% of the earth is comprised of water. The remaining 25% of it is land but not all of it is soil. About 12.5% of this is either deserts or mountains, both of which are unsuitable for agriculture, 5% of it is rocky and low-quality terrain, which leaves only 7.5% of land which has "agriculturally-suitable" soil for farming (Moore et al., 2019). This means that the available area for growing food crops to feed an ever-increasing population is already scarce and we cannot afford to lose any more of it.

What Is Soil?

Soil is the most critical natural resource, one that creates and maintains life. It contains both organic and inorganic components. The reason soil is identified as “alive” is due to the large number of living organisms dwelling within it, the biochemical activities that go on inside the soil make it the most biologically active natural resource on planet earth. All organic life, including humans, animals, plants, viruses, fungi and bacteria, are created and sustained by and through the earth’s soil. You would think that soil is solid (amorphous) in nature, but that’s not true! Soil has all three states of matter which are soil, liquid and gas. The mineral and organic content in it constitutes the solid portion of the soil. The “soil solution” is the liquid part of the soil that plants and other living organisms use to derive water. The “soil environment” is the air around the soil particles that plants and microbes use for gaseous exchange.

Soil is organic seen through the lens of a biologist (or microscope). However, it is inorganic in biophysics and chemistry textbooks and it is a valuable resource in the context of agronomy. In the last few decades, people have completely overlooked soil as organic matter. Soil has mainly been seen as a source medium for food and fuel while completely ignoring its organic side. Today’s scientists know little about the biochemical activity that goes on in the soil. Segregating our knowledge about soil into Soil Biology, Soil Biophysics, Agronomy and Soil Chemistry has hindered our view of the big picture of what soil is. In this book we will uncover all of the links that connect different soil sciences to help you see the bigger picture of the soil’s importance.

Soil Characterization

Since soil has a very diverse nature, it cannot be identified based only on a few essential criteria. Soil scientists use a total of six criteria to characterize soil samples:

1. Texture

The soil's texture depends on the type of mineral particles present in it. The nature and properties of these minerals are in turn determined by their parent material and the environmental and geological conditions under which the soil is formed. Texture determines the overall structure, density, and water retention capacity of the soil.

The most important inorganic particles that determine the soil texture are listed below in decreasing order of their particle size.

Gravel

Gravel is a loose assemblage of tiny rocks and pebbles ranging in size from small stones (about 2 mm) to boulders (about 250 mm). Gravel is rich in heavy metals and mineral ores indigenous to its origin area.

Sand

Sand particles are biochemically less active than other soil constituents. These particles range in size from 0.02 mm to 2 mm. Sand particles have a small surface area-to-weight ratio, and it has the lowest water retention capacity. Quartz is the most common mineral found in sand fractions.

Silt

Silt particles range in size between sand and clay particles. Silt most commonly contains broken grains of quartz and feldspar. It is normally a highly mobile, fine powder when dry, but it becomes denser in wet conditions. Silt sediments easily, and this affects the free diffusion of water and air in the soil. However, the fertility of riverbeds is due to their rapidly shifting silt deposits. These silt deposits actively replenish essential nutrients in the soil.

Clay

Clay particles are smaller than all other soil components. These particles are less than 0.002 mm in diameter. In contrast to other soil components, clay particles have a large surface area which makes them a good carrier for nutrient molecules. These molecules, when mixed in "soil solution," are easily taken up by the plants. Clay particles have a high affinity for water, but this water is not easily accessible to the plants. The parent material of clay is silicate, although it also contains small quantities of quartz, metals, and some water molecules. Clay swells and becomes sticky when wet, which helps the soil in retaining its shape.

2. Color

The color of soil is a big indicator of its organic content, water retention and drainage capacity, which in turn indicates its fertility. Soil that has undergone extreme weathering can be identified through its color, for instance, yellow-colored soil is the least weathered. As a general rule, dark-colored soil is considered the most fertile because of its high organic content. The dark brown color has the highest organic content, while the blackish color indicates the presence of humus. Red-colored soils are rich in iron and are good at draining water. Contrastingly, a yellow color indicates poor drainage. Gray-green soil or blue soil hues indicate problematic soil, and these soils have water logging issues.

3. Depth

Soil depth is yet another soil feature that determines the accessibility of nutrients and water to plants. A suitable depth for a plant is defined as the vertical distance from the top of the soil to the point into the soil where the growth of the roots effectively stops. The depth of the soil determines its nutrient and water retention capacity. Deeper soil is considered better because it allows roots to grow freely, provides anchorage, and offers better drainage. Shallow soils can support annuals that require little or no irrigation, but perennials and deep-rooted woody plants require deeper soils. Such plants cannot thrive in shallow soil where the nutrients are scarce and the space for vertical root development is so little.

According to Oregon State University (2016), the soil is considered:

- very shallow-the depth is less than 10 inches.
- shallow- the depth is between 10-20 inches.
- moderately deep- the depth is between 20-36 inches.
- deep- the depth is between 30-60 inches.
- very deep- the depth is more than 60 inches.

4. Porosity

Soil porosity is a measure of the number and size of pores that exist between soil particles. Soil porosity is directly related to water drainage. For soil to have good drainage, the pores should be large and few in number. Besides the natural structure of the soil, several other factors affect porosity:

- Earthworm activity increases pore size.
- Root development is known to soften compacted soil by creating new pores.
- Excessive cultivation is known to break soil aggregates and cause soil compaction by removing pores between soil particles.
- Extremely high pressure and heavy traffic causes soil compaction.

5. Structure

Soil structure is the most important soil characteristic that determines soil health and the free movement of air and water molecules within the soil. The structure of the soil is composed of soil aggregates which may vary in size, shape, and strength.

A soil aggregate contains all the mineral components of soil, i.e., gravel, sand, silt, and clay along with organic molecules. Organic matter and calcium ions provide the adhesion to hold the aggregate together. Since this adhesion is not very strong, the soil structure can easily collapse due to weathering, tilling, and other physical changes. Other physical pressures, like excessive traffic, can cause soil structure to collapse, and the resulting compression can create a hindrance in the transport of water, air, and nutrients.

Perfect soil has the best soil structure and is a free draining soil. Unfortunately, finding both of these features together is not common. Some soil has the perfect soil structure but doesn’t allow free-drainage, while others are free-draining but do not have a decent soil structure. For instance, the soils containing more clay content have good soil structure but their drainage is low. Similarly, sandy soil scores low in soil structure but has extremely good drainage.

Soil structure can be further classified as crumbly, massive, cloddy, and platy and can be assessed by acquiring a soil cross-section. To gain an understanding of the structure and strength of your topsoil, you can dig a small hole 20-30cm deep. Once the hole is dug, take a slice off the side and lift it out, keeping it intact. Lay the slice on its side to examine it. Crumbly soils tend to be softer and more conducive to root and shoot development than massive, cloddy, or platy soils. Massive soils have particles of the same size that lack soil structure and arrangement, such as sandy soils. Cloddy soils break into large clods and are hard to break down, and platey soils break apart into flat, plate-like layers similar to soil crusts.

6. Stone Content

The stone content of a soil sample is the measure of the total mass and volume of stones present in it. Stones that are larger than 2 mm are also included in this type of soil content. Determination of soil content is important when determining soil quality. That’s because stones do not contribute to the overall nutrient or water supply capacity of the soil and therefore must be excluded from the total soil mass and volume.

Adding small-sized stones in little amounts to highly-compacted silty soil is known to decrease its compatibility while increasing its porosity and permeability (Shakoor & Cook, 1990).

The History Behind Soil

The geological activity on earth started long before any form of life appeared. According to an estimate, the first rocks and sediments appeared almost 2 billion years ago. Since then, the land has been subjected to various geological changes (both slow and rapid) and these changes have slowly formed the soil as we know it now.

Geologists divide the soil geological history into two distinct stages/periods:

1. **Pre-Cambrian Period**

The Pre-Cambrian period dates back to 2 billion years ago (*The Beginning of Soil*, n.d.). During this time, we have no evidence that any life existed on Earth. Therefore, any soil that existed would have been devoid of organic matter and would have consisted of a sterile mixture of rock and dust. Since this soil was formed in the absence of oxygen and water, it had a green color and a powdery form.

1. **Devonian Period**

The Devonian period dates back to 400 million years ago (*The Beginning of Soil,* n.d.). During this time life started to appear on Earth. The first animals and plants started to interact with soil and the organic content began to develop. This led to the change in soil coloration from green to reddish brown. Photosynthetic plants gradually increased the oxygen reserves and that's when the living soils started to develop.

Since their beginning, humans have had a deep connection with the soil. The hunter and gatherer societies relied on everything that was in and on the land for their sustenance and survival. Hunting didn't always ensure a constant food supply, and they couldn't always rely on wild fruits and berries, which are logical reasons why they decided to learn to farm and grow their food. Humans knowledge of agriculture gradually grew to include the knowledge of manure applications, irrigation, and the use of terraced land, and the best seeds to obtain an optimum yield.

The earliest known record of agricultural practices dates back to 11,000 B.C.E. in Iraq where practices like tilling and land testing were employed to get the most fertile soil for farming (Brevik, n.d.). Signs of primitive irrigation systems were also found In Iraq. The Mesopotamian civilization (in present-day Iraq) that settled between the Tigris and Euphrates rivers was the first to show an understanding of "soil science."

The early civilizations of the Greeks and Romans were found to know a great deal about different types of soils and soil profiles. They had a clear understanding of the role of soil nutrients in determining plant productivity. Greek scholar Theophrastus was the first to present the agronomic classification of different soils in his book "On the Causes of Plants." In the 1st century B.C.E, Chinese Fan Shengzhi presented his findings on the topics of plowing, irrigation, harvesting, and field usage. The Chinese did a lot of work in the field of soil fertility and land usage, but their work lacked experimental verification. Cato, a Roman aristocrat and analyst, introduced the usage of manure to improve soil fertility. The Egyptians were not as advanced as the Greeks, but they were well aware of the importance of silt that kept their valley fertile. They also knew about the methods to remove undesired salts from the soil. Lastly, in Asia, the civilizations that flourished around the Yellow River, Indus River, and Kabul River had developed sophisticated ways to maintain the fertility of their soil, and their knowledge of soil science helped them attain optimum yield from their lands.

Famous Soil Science Discoveries

"Real" work in the field of soil science began in the Renaissance in the 16th century when, for the first time, people began experimenting and researching soil and soil components. This is a time period where we have records showing that scientists began working on soil microbes. The discovery of the microscope completely changed the way people looked at the world. This discovery propelled the research in soil science.

Renaissance scholars like Leonardo da Vinci and Robert Boyle did their best to change peoples' views of soil fertility, soil composition, and plant-soil relationship even in the absence of sophisticated scientific tools. A major advancement began in the 19th century when Russian geologist Vasily Dokuchaev (1846-1903) proposed that soil is a living system. He categorized soil science as a branch of biology. His ideas sparked interest amongst the scientists who, until then, considered soil a mere medium for supporting and nourishing other forms of life. His revolutionary ideas earned him the title "father of soil science" (*The History of Soil Science*, n.d.). According to Dokuchaev, the geographical variation in soil type and structure is not only created by different geological factors (formation-related), but also by varying biological, topological, and climatic factors.

After the influential work of Dokuchaev, scientists started exploring the chemistry and microbiology of the soil. In 1753, manure was classified for the first time and the composition of humus was determined as a result of these efforts (The History of Soil Science, n.d.). In the 19th century, Albrecht Thaer explained the difference between peat and humus in his *Humus Theory*. He also advocated the idea of crop rotation. His reputation earned him the title " father of sustainable agriculture."

Between 1900-1910, advancing microscopy helped microbiologists study several types of beneficial bacteria and fungi, which emphasized the importance of soil's organic matter. The advancing of microscopy also led to the division of soil scientists based on their ideologies, soil microbiologists and soil geologists being the two major groups. While the geologists were interested in exploring soil in its full heterogeneity, microbiologists preferred studying the soil microbes under lab conditions only. These differences exist even today. Microbiologists have turned their attention completely to the exploitation and modification of microbes to improve plant productivity while regenerative agricultural practices have been ignored.

How Is Soil Formed?

As stated earlier, the soil that we find currently wasn't present at the beginning of the Earth's existence. It took billions of years before a soil composition suitable for both plants and microorganisms to live in it had formed. Also, it was not just the layering of the mineral components that created the soil. In fact, several geological, environmental, and biological factors have played crucial roles too. These factors include parental materials, climate, living organisms, topography, and time. All of these factors determine the physical, chemical, and biological nature of the soil.

Parent Material

Parent material is rock or the sediment that provides the basic mineral content for soil. The composition of the parent material influences the mineral composition and structure of the soil. Weathering is a force that breaks down rock to create sediment, which then combines with other mineral and organic matter to create "living" soil. Geologists have divided rocks into three broad categories based on their formation. These are named igneous, sedimentary, and metamorphic rocks.

- Igneous rocks are the ones that are formed through the hardening and setting of erupted lava or magma. Silicon is the most common element in these rocks.
- Sedimentary rocks are formed through the compaction and cementation of sediments and rocks that build up over time. Since these are composed of sediments, they are the most diverse form of rocks.
- Metamorphic rocks are created when rocks (belonging to all three categories) are subjected to extreme geological pressures.

Climate

After parent material, climate is the greatest influencing factor that determines the strength, structure, and composition of the soil. Climatic variations determine the intensity of weathering that takes place and are also responsible for controlling the kinds of plants and other organic matter that grow and settle in and on the soil. Hot and humid areas are bound to have better plant growth so the soils in these areas are nutrient-rich and full of organic matter.

Contrastingly, the soil that exists in cold areas has little vegetation and the microbes that thrive in this soil are well-adapted to the cold environment. The amount of rain and snowfall that a region receives is also determined by its climate and affects the soil. Rainwater allows the minerals present on the top to seep into the lower soil layers. Likewise, the periodic freezing and melting of rainwater between the rock cracks lead to the breakage of rocks into the sediment.

Living Organisms

Living organisms include indigenous plants, animals, and decomposers that interact with other factors like climate, topology, and soil's parent material to determine the structure and composition of the soil. The fertility of the soil is directly dependent on these organisms. As mentioned earlier, the climate of a region determines its flora and fauna. The decomposition of dead plants and animals by the decomposers like bacteria, fungi, and earthworms adds humus to the soil. An abundance of roots and humus in the soil is known to lower soil erosion by keeping the soil structure intact.

Topography

Topography is the setting of the physical features of an area, and it plays a crucial role in what physical and chemical features are found in the soil. The topography of an area includes the immediate environment that is in contact with the soil.

The elevation and steepness of the land are important factors too because it affects weathering impacts on the soil. In high-altitude and steeper land areas, the water flows forcefully downward, taking the nutrients and minerals with it. Such soil is less fertile, especially when the vegetation is scarce and there is nothing to hold the soil together.

Low-lying soils that are well-covered by plants are less exposed to weathering changes. This means that these soils are not changing rapidly by weathering or erosion. Plus, with the water table, an area below the surface of the soil but above the saturation zone , within close proximity, these soils are even more fertile.

Time

With just the right combination of the above-mentioned factors (parent material, climate, topography, and living organisms), time acts as a catalyst for perfect soil formation. In the presence of crop cover, favorable climate conditions, and an abundance of mineral and organic components, a fertile soil profile is generated over time. Alternatively, in the absence or scarcity of this factor, soil formation takes a lot more time and is low in fertility.

All of the above-mentioned factors interacting together determine the quality, depth, and duration of soil formation. Among these factors, living organisms and climate are the most crucial factors; they influence the beginning and end of soil formation. Parent material and topography are crucial in the starting phase, while only time defines the duration that it takes to form a soil of desirable qualities. In short, the soil that we have now is a result of numerous microscopic and macroscopic phenomena.

Over time drastic weathering and climatic conditions create sediment. This sediment either stays in one place or is eroded to a different place. Once it has settled in a place, vegetation starts to appear on it and microbes start colonizing it for food and shelter. As soon as the plants die, decomposers degrade them, thus adding organic matter to the soil. At the same time, animals' activities return nutrients that were perviously taken, back into the soil. Physical forces like wind and water continue to erode and replace soil layers and so the process continues.

Soil formation leads to the arrangement of soil in the form of several distinct layers. These layers are formed because of the layering that occurs over hundreds of years. These soil layers (from bottom to top) are

1. Bedrock—the rock that lies at the base of soft parent material.
2. Regolith—the layer on top of bedrock that contains crushed parent material, sand, and dust all of which provide a base for upper layers of soil.
3. Subsoil—the thickest layer of sand, silt, and clay that lies on top of Regolith
4. Eluviation—a thin layer that transports nutrients between upper and lower layers of soil.
5. Topsoil—the topmost layer that is rich in microorganisms and other organic matter.
6. Humus—the organic matter that lies on top of the topsoil and provides nutrients to the lower layers as well as increases their water retention capacity.

The soil formation that we have covered so far is naturally-occurring and has occurred for several billions of years since its beginning. Unfortunately, human activities and related climate changes such as, overgrazing by livestock, deforestation, erosion, urban and industrial development, and excessive use of chemical fertilizers and pesticides have started meddling with this process and has caused damage to the soil—both reversible and irreversible.

Different Soil Types

Categorization of soils into different types is a way to determine their pros and cons. This is determined based on the soil particles that are most abundant in these soils. When selecting the best soil for plants, soil type is the first criterion to consider. There are six basic soil types:

Clay Soil

Clay soil is soil that contains 25% clay (Boughton, 2019). Since clay has the smallest particle size and surface area, the particles in this type of soil are held together tightly. Therefore, the pore size as well as the availability of air is negligible. The lack of porosity in clay is why it holds water so well and for a long time; however, the entry and exchange of air is limited. Clay soils do not allow plant roots to flourish very well.

Silt Soil

Silty soils are found commonly near water bodies. Silty soils are composed of medium-sized particles that sediment easily and their water drainage capacity is high, but they will hold some of the moisture too. Because of silty soil's capability to drain water well and its high mineral content, it ranks high in the fertility index. The downside to silty soils is that it can be displaced easily by rain or wind. To prevent displacement, mixing silt soil with a small amount of organic content provides a solid structure and strength.

Sand Soil

Sandy soils are rich in quartz and granite. Sandy soils are lightweight and warm up easily. Water drainage is also very high in sandy soils. These qualities seem desirable, though, low water retention and weak soil structure make it a poor choice for growing plants. Such soils rank low in the fertility index because their structure is too weak to hold the nutrients which are easily eroded by wind and water. Just like silty soil, adding organic matter can provide firmness and improve the nutrient-holding capacity of sandy soil.

Loam Soil

Loam soil refers to a combination of sand, silt, and clay. As mentioned above, each of these soils have their pros and cons; however, combining these soils eliminates most negative effects. As a result, the loam produced from the combined soils has all the desirable qualities that make it the perfect soil for plant growth. It is easy to handle, has good drainage, has sufficient water retention, and has a perfect balance of organic and inorganic material. Additionally, loam soil contains humus which makes it even more fertile. Loam is known as the gardener's best friend because it is suitable to grow almost everything.

Peat Soil

Peat soil is a highly fertile form of soil that is rich in organic content. It has a high amount of beneficial bacteria that are favorable to plant roots. Its structure allows for high moisture retention. This kind of soil is commonly present in the wetlands like moors, swamps, and bogs. It is often used by gardeners to provide a head start to their plants.

Chalk Soil

Chalk soil is soil that contains high quantities of calcium carbonate (limestone). The presence of calcium carbonate makes it highly alkaline. Chalk soil is great for growing "lime-loving" plants like beans, peas, onions, garlic, parsnips and spinach.

What's Causing the Damage to Soil?

Soil formation is not a one-time process. Even when all soil layers are completely formed, physical and biochemical processes continue to change it. Rain and wind first erode the surface of the soil, and then the decomposition of plants and animals refurbishes the soil layers. The soil nutrients that are used by the plants are ultimately returned to the soil through biogeochemical cycles. This is how the Earth replenishes and maintains soil in its original form.

However, during the last 100 years, human activities have become so much more exploitative that they have started to damage the quality and quantity of the soil. One of the biggest pieces of evidence of this change is the current state of soil in Iowa.

The soil in Iowa was once called “black gold” due to its rich organic content that contributed to its fertility. This made Iowa the biggest producer of soybean, corn, and oats in all of the U.S. This is currently no longer the case because of the reduction in soil quality–and quantity.

According to Veenstra (2010), the organic matter in the soil of Iowa has lowered drastically since 1959 in addition to soil structure degradation. In several areas, the depth of topsoil has decreased by half. Excessive tilling and degenerative agriculture practices in combination with extreme climate events are the main contributing factors. The changes occurring in the soil of Iowa are alarming, not new. Soil scientists have noticed the same effects in soils all over the world. An overview of the scientific data suggests that

- excessive tilling and plowing has damaged soil structure in many agricultural areas.
- monoculture, the continuous growth of one crop in the same area, has stripped away essential nutrients from the soils turning them into barren lands
- poor water management practices and increased amounts of rainfall in certain areas have waterlogged the land.
- excessive use of chemical fertilizers has affected the soil’s pH while also disturbing the indigenous microbes present in it.
- water and land pollution have rendered the soil uncultivable in many areas.
- the deforestation caused by urbanization and industrial activity has exposed soil to erosion causing large amounts of soil along with its essential nutrients to wash away into water bodies.

And the saddest part is even after knowing all this, people have turned a blind eye toward this issue. The UN’s Food and Agricultural Organization (FAO) warns that if we continue on the current path, the world will run out of topsoil in the next 60 years.

You’d think the only issue that soil degradation creates is that of food security, but that's not all. Besides food security, the world faces higher threats of food-borne illnesses. Crops grown in the presence of chemical fertilizers are likely to cause severe health issues. Higher proportions of wind-eroded dust in the air will cause respiratory problems and eye-related diseases. The scarcity of agriculturally suitable land will create conflicts and mass migrations. Ecosystems' destruction will cause the displacement and extinction of several species. Global warming will be exacerbated too.

The effects discussed above are not expected to happen in the future—they are already happening. According to the estimates by FAO, one-third of the Earth’s soil is already partially or fully degraded (Food and Agriculture Organization of the United Nations, 2019). In short, the future of the world looks bleak without healthy soil. The situation is dire and demands emergency response not only from the world governments but from everyone including you!

2

SOIL ORGANIC MATTER

After learning about the devastating soil situation, eco-guilt might be taking hold, and you might be thinking of quick ways you can remedy your contribution. You might even be thinking of getting a bag of organic fertilizer for your garden—because what's better for soil than nutrient replenishment? But quick actions like that are premature without understanding the basics of soil science. Remediation of soil is possible only after we have understood the root cause of the problem.

Labeling soil "alive" means that it has an abundance of living matter inside of it, and it is this living matter that makes the soil a multipurpose entity. According to Wagg et al. (2014), 1 g of soil has 1 billion bacteria belonging to a thousand different taxa, about 200 million fungal hyphae, and a huge amount of decomposers and arthropods. The role of this biodiversity in supporting and sustaining the ecosystems above soil is not fully understood; however, these living organisms play a crucial role in the smooth execution of the biogeochemical cycles, including carbon and water cycles. Through these biogeochemical cycles, soil and its organic matter play a vital role in sustaining plants and animals within their ecosystems.

The Organic Side of our Soil

Normally, organic matter (OM) is not considered a vital part of soil structure because of the fact that it exists in very small amounts in the soil. However, in terms of its effect, OM is the most important portion of the soil.

What is Organic Matter?

Merriam-Webster defines the word *organic* as "of, relating to, or derived from living organisms," as well as "of, relating to, or containing carbon compounds." In view of these definitions, we can conclude that OM is any material composed of and by living organisms. This includes living soil microbes to dead plants and animals (both partially or fully decomposed). All of these constituents are carbon-based, the base of all living systems. Besides carbon, other elements present are oxygen, hydrogen, nitrogen, phosphorus, sulfur, potassium, calcium, and magnesium. These elements are involved in the formation of biomolecules like carbohydrates, proteins, lipids, and nucleic acids.

The decomposition of plants and animals breaks down their biomolecules to release simpler constituent elements, which then become part of the soil. These elements are either assimilated with the soil or washed away into water bodies. In both cases, these elements serve as the base for the growth and sustenance of new plants and animals. The death and decomposition of plants and animals return the nutrients back to the soil in the form of OM, and so the cycle continues.

The highest percentage of OM comes from plants. Plant tissues have 60–90 percent moisture content; however, the dry plant tissues contain all of the elements mentioned above. Even when the percentage of these elements is not significant, they play a monumental role in determining soil fertility. At any time, a flourishing mix of OM contains both active and resistant organic matter. Active organic matter includes

- microscopic plants
- fungi
- algae
- bacteria

This active matter constitutes 10%–40% of organic matter while the resistant organic matter which is 40%–60% of OM at any time consists of (The Importance of Soil Organic Matter, n.d.-a):

- dead plants, plant parts, and fallen leaves
- dead animal tissues
- partially degraded plant and animal tissues
- grass
- crop residues

These are collectively known as humus.

Another classification of OM is based on location. It divides OM into aboveground and belowground fractions. Aboveground fractions naturally include plant and animal residues that are intact and require decomposition for transition to humus. Belowground fractions include all kinds of inground flora, fauna (both live and degraded), decomposed plant and animal tissues, and microorganisms.

Even when OM can be divided into distinct fractions at a given time, this does not mean that the amounts of these fractions are going to stay the same. These fractions are continually changing as the process of decomposition continues. For instance, if a soil sample has an aboveground fraction of 38% and a belowground fraction of 62% at one point, these fractions are likely to change with time; the aboveground fraction will decrease as more of it is decomposed to resistant OM.

How Is Organic Matter Formed?

The formation of OM is a dynamic process that involves the transformation of several elements through physical and biochemical methods.

Dead plants, plant parts, grasses, yard clippings, and crop residues make up the largest part of OM. The relative speed of the decomposition of these constituents depends on the carbon-to-nitrogen ratio (C:N). A high C:N ration means the material is more resistant to decomposition. Woody parts of plants have a high C:N ratio. Green portions with low C:N ratio are an easy target for decomposers. Plant residues are broken down into smaller pieces through a combination of physical and biological processes. Then the plant residues are decomposed until they release biomolecules like cellulose, starch, and lignin. Further processing of these molecules produces long-chain carbon molecules which are then shuttled into biogeochemical cycles. Other trace elements produced during their decomposition are used to improve the nutrient profile of the soil.

Other than plant and plant products, recently added dead animal tissues, animal manure, microorganisms, insects, and earthworms provide substrates for OM formation. Their decomposition leads to the release of biomolecules like proteins, carbohydrates, and lipids. These molecules are referred to as the non-humic organic fraction of OM, which is easily degraded by soil organisms. These molecules also contain carbon chains with elements like oxygen, hydrogen, nitrogen, phosphorus, and sulfur attached to them. The complexity of their structures determines their ease of decomposition. Sugar and starches are decomposed easily, while fats and waxes require a longer time for complete degradation. Besides non-humic fractions, the humified OM or humus is the portion that is not degraded by microorganisms because of its complex structure. Humus is the main part of OM that performs most of its functions.

The living components of OM that perform the decomposition of the dead plant and animal matter are mostly located belowground. These include bacteria, viruses, algae, fungi, protozoa, micro-arthropods and other insects like earthworms. Burrowing animals like rabbits and mice are included in the list too. Another interesting living component of OM is living roots which are responsible for churning the organic matter within the mineral soil. Microorganisms and insects perform the decomposition of animal and plant residues by ingesting and transforming them to release new nutrients within the soil. To keep the particles of OM together, the sticky “glue” released by bacteria and fungi is used. Aside from that, the sticky bodies of earthworms help to aggregate these particles together.

The quantity and overall distribution of OM in the soil is dependent on several factors. The most important of these factors is the periodic input of dead matter, which provides substrates for a new OM formation. Besides this, the soil structure also plays a role in deciding how well the OM is mixed in the soil. Both of these factors are dependent on the ecology, pH, climate, temperature, aeration, and moisture level of a region in which soil is located.

The Importance of Organic Matter

The importance of OM for soil cannot be overemphasized. It not only performs important functions on the surface but also keeps the core of the soil warm, moist, and full of nutrients. Let’s see how that happens:

- OM residues that exist on the soil surface prevent erosion by providing a cushion against rainfall and wind. Soil that has lower organic content due to exploitative agricultural practices and extreme climatic events is more prone to erosion.
- OM actively performs nutrient cycling. Being a crucial part of biogeochemical cycles, it carries out the transfer of carbon, hydrogen, oxygen, and nitrogen from the atmosphere to the soil and back again.
- OM is a storehouse of essential plant nutrients owing to the fact that it is primarily created from decomposed plant residues. These nutrients reside in the humus ready for uptake by plant roots.
- All of the active OM and a few components of resistant OM are involved in gluing the

soil particles together to form aggregates. As mentioned earlier, aggregation is an important feature of soil structure that helps in maintaining good aeration, moisture retention, and resistance to erosion.

- Resistant organic fraction is also responsible for maintaining the nutrient retention and nutrient exchange process via its cation exchange capacity (CEC). CEC is the measure of the positive ion retention capacity of any material. An abundance of negative charges on the surface of OM particles allows them to attach positively-charged nutrient molecules on their surface. These nutrient particles are easily exchangeable with other positively-charged molecules present in soil solutions. This way nutrient molecules are easily dissolved in water and made accessible to the plants.
- Do you know what contributes most to the soil color? That's OM, again! The dark-colored soil that you see in most fertile soils comes from the OM in it.
- Soil aggregation that occurs in the presence of higher organic content allows more water to infiltrate. Water runoff is also decreased. The water retention capacity of OM is 10 to 1,000 times higher than mineral components of soil.
- An overall increase in the organic content of the soil also means that the population and diversity of soil microorganisms are improved, which speeds up the decomposition of organic content.
- In the long run, rich organic soils contribute to soil fertility and improved productivity.
- Reduced water loss through runoff means that the soil is better equipped to withstand droughts.
- OM may also keep harmful chemical fertilizers from getting into the soil, thus acting as a soil filter.
- Soils rich in organic matter also have higher decomposition activity that effectively tends to the animal and plant residue present on the surface. In this way, OM performs effective waste management for the ecosystem.
- Humic parts of OM are also implicated in improved fertilizer uptake, increased life of nitrogen fertilizers, and increased uptake of phosphorus and calcium.
- Humus effectively manages soil salinity by acting as a buffer between sodium deposits. It also improves the carbon reserves of soil.

Factors Affecting the Organic Content of Soil

While there are several aspects of soil that are influenced by OM, sometimes OM is influenced by these aspects mostly in the form of feedback regulation.

Soil Organisms

We have previously learned how the presence of organic substrates improves the population and diversity of microorganisms in the soil. In the feedback regulation of this interaction, the microorganisms' activity causes an increased OM production by speeding up the decomposition process. This is based on the principle of the nutrient-cycling system which is balanced between the addition of organic residues and their decomposition to the OM (plus its uptake by plants and loss through erosion and leaching). When both of these processes are occurring at an equal pace, the amount of OM in the soil stays unchanged. However, when the speed of organic residue replenishment exceeds the speed of decomposition, the overall OM increases in the soil.

In addition, the activity of soil organisms is also dependent on crop seasons. This means that they are not equally distributed all year long. The population of rhizosphere bacteria that reside primarily in the roots is especially affected by these crop seasons. To sustain the population of such bacteria, minimum or no disturbance of soil structure is suggested. Leaving crop residues on the soil after crop harvesting may also help sustain their population. For these reasons, minimum to no tillage is suggested as the best way to maintain the highest levels of OM in the soil. This is particularly important for human-managed systems.

Temperature

Temperature is another important factor that determines the rate of OM formation. With every increase of 8–9 °C (46.4–48.2 °F), the decomposition rate of organic residue doubles. This means that decomposition rates are higher in the tropics than the temperate regions. Nevertheless, to sustain a continuous production of OM, a periodic addition of organic residue is essential.

Moisture Content

OM production is also directly related to moisture content. Areas that receive higher precipitation are likely to have more biodiversity both aboveground and belowground. This means that both the organic residues (on the soil) and soil microorganisms (in the soil) are high, thus providing a higher OM production rate. Along with higher moisture levels, the soil's drainage should also be high because water saturation can lead to oxygen deficiency in soil and, ultimately, the death of essential soil organisms.

Soil Structure

Soil texture is also an important factor that determines OM development by affecting the growth of soil microbes. Soils with higher clay content tend to have more organic matter. This is because the soil that has higher clay content is more likely to form stable soil aggregates, which decelerates the process of decomposition.

Chemical Properties of the Soil

As far as the chemical properties of soil are concerned, organic matter is favored by "neutral soil." Any soil that has high salinity or extreme pH conditions are low in organic matter. Bacteria and fungi that are sensitive to extreme pH and salt conditions are inhibited and so is the speed of decomposition.

Topography

Low-lying and well-covered soil always favors OM production. This is because such soils are less exposed to erosion; plus, they receive the highest proportion of organic residue through landscape runoff and erosion.

The OM is the lifeline of soil. Human activities and aggravating climate disasters are meddling with this lifeline, and the intention of this book is to reduce these interruptions, which is discussed further in part II.

A Refresh on the Water Cycle

Do you recall the biogeochemical cycles that you learned in school? They were fun to learn, weren't they? Back in my school days, I learned that these cycles are not *just* nutrient transport cycles, these are the “cycles of life.” They are propelling life on earth, and if they cease, life on earth would cease to exist. I hope they still teach about these cycles and their vitality because it seems like most people have completely forgotten those lessons. I am astounded to see how human actions, without considering the consequences, are disrupting the flow of these cycles.

I hope you remember the first and easiest cycle you studied in your school days. You guessed it: the water cycle. Let’s quickly review the principles of this cycle.

The water cycle is the process that involves the constant cycling of water between the soil and the atmosphere. The total water in the system remains the same; however, its distribution within different parts varies continually. The main processes below are involved in the water or hydrological cycle:

- Evaporation—evaporation happens when water from land moves to the atmosphere in the form of water vapors. Temperature and pressure are important factors that determine the rate of evaporation. Most of the water that rises through evaporation comes from the oceans.
- Transpiration—transpiration is the loss of water through aerial parts of plants. This water is lost through tiny pores called stomata that are present on the surface of the leaves and stems of plants. Remember, transpiration also creates a pull that draws minerals from plant roots to its leaves.
- Sublimation—the direct conversion of ice and snow to vapors is termed sublimation. This process instantly creates clouds.
- Condensation—water vapors rise in the air through evaporation, transpiration, and sublimation, and then condenses to form rain clouds.
- Precipitation—this refers to the return of water to the land in the form of rain, or snow. Coastal areas and areas with dense vegetation are more likely to receive precipitation because of frequent transpiration and cloud formation.
- Deposition—the instantaneous conversion of water vapors to snow is called deposition. This is the opposite of sublimation.
- Runoff—rainwater that reaches the earth flows down steep terrain towards the coastal areas, bringing vital minerals and salts with it. Runoff plays an important role in the transport of minerals and nutrients from one place to another.
- Infiltration—infiltration is when water soaks into the soil through its pores and cracks. The rate of infiltration varies for different soils based on their surface.
- Percolation—this is the vertical movement of water through soil structure. This includes the water transfer from roots to the water table. The speed of percolation is a lot slower compared to the speed of on-ground water.

Continuation of all of these steps in a periodic manner results in a seamless water cycle. One major constituent of water cycles maintaining a balance between water on earth and the atmosphere is ice in the form of sea ice and ice glaciers. Water that exists as ice stays away from the active water cycle for a long time before it finally melts to enter the “running stream.” Several thousand years ago, approximately 30% of the land was covered in ice. Only 12% of it remains today (Editors of Encyclopaedia Britannica, 2019). This change has not only disturbed the balance of the water cycle but has contributed to most of our climate problems.

How Humans Have Disturbed the Water Cycle?

We may have started with the “fair-usage policy” of earth’s resources, but with population growth and technological advancement, the rate at which natural resources are used is exploited and mismanaged. The same is the case with water consumption. While the list of how these resources are mismanaged is a long one, let us start with the biggest one: hydropower production.

Hydroelectricity Generation

We all probably learned in school that hydropower is the perfect way to generate electricity without causing any environmental impacts. But that’s not entirely true! Although hydroelectricity is a renewable energy, the dams built for electricity generation do have deep impacts on surrounding ecosystems. When dams are built on rivers for water storage, the soil chemistry and biodiversity are disturbed both upstream and downstream. We have discussed how water runoff produces gravel for soil formation and how this water transports vital minerals from one place to another. When water is banked by dams, all of the silt aggregates upstream while the downstream areas suffer from mineral deficiency, which impacts their fertility and productivity. The formation of new soil layers is also disturbed. Flora and fauna may flourish upstream while, at the same time, plants and animals downstream face serious problems, especially small streams that dry up or decrease in vegetation.

Crop Irrigation Systems

With time, irrigation systems have become a vital part of our agricultural practices. While these systems provide water to the arid lands, there is a cascade of problems that come along with them. First, these systems remove the water from its source which has deep impacts on the overall function of the water cycle. Runoff from irrigation water extracts essential nutrients from the soil, which lowers its fertility. This compels the farmers to use fertilizers, which in turn pollute the water even more.

I remember learning about the vitality of irrigation systems in my geography class in school, but nobody told me that this “efficient and farmer-friendly” system comes at a high cost.

Deforestation

Large-scale deforestation followed by urbanization severely affects the climate and annual rainfall that an area receives. This occurs because the removal of trees from these areas interrupts critical processes of the water cycle including transpiration, condensation, and precipitation. The lack of trees also lowers the water retention of the soil. And the little rainwater that these areas do receive is lost as runoff. This increases the chances of floods, droughts, and soil erosion.

Climate Change and Global Warming

This is perhaps the greatest fallout of human activities that has disturbed the flow of the water cycle. Increasing levels of carbon dioxide and the resulting long-term shifts in weather patterns have drastically affected the water cycle at several stages. Glaciers that were dormant for several centuries are starting to melt, causing the ocean levels to rise and annual rainfall to increase. This has led to floods in some areas and droughts in others. Events like these have not only affected the human populations but also the soil in several areas. Thousands of hectares of agricultural land have been turned to waste due to salinity, acidity, and leaching of vital soil components. In the long run, these stresses on the hydrological cycle are damaging the liveability of the earth not only for us but animals and plants too.

The Mineral Cycles

Besides the water cycle, there are several other mineral cycles that explain the cycling of vital elements (and their compounds) between different parts of ecological systems. These cycles include

- oxygen cycle
- nitrogen cycle
- phosphorus cycle
- sulfur cycle

Let’s take a look at how their cycling works.

The Oxygen Cycle

Oxygen is an important constituent of organic compounds, which means that it is crucial for the construction and sustenance of life on earth. Oxygen cycles continuously between the land, the atmosphere, and living things in the form of complex compounds composed of oxygen and other elements. At any instant, 21% of oxygen is present in the atmosphere and 20.6% in the soil (NASA Global Climate Change, 2016; Soilsportal, 2022b). Common compounds in which oxygen combines together with other elements include carbon dioxide, water, carbonates, and nitrates.

Oxygen molecules in carbon dioxide when reacted with calcium, nitrogen, and iron are converted into carbonates, nitrates, and ferric oxides respectively. These compounds are actively taken up by the soil where they improve the nutrient profile of the soil. Plants uptake these compounds for growth and metabolism. During photosynthesis, oxygen is released into the atmosphere. Plants and animals use this oxygen to generate energy during respiration and ultimately convert this oxygen to carbon dioxide and water which are released into the atmosphere. Numerous aerobic microorganisms use oxygen to decompose organic matter back to simpler compounds. Lastly, the surplus air that reaches the stratosphere is converted to ozone. This is how the levels of oxygen in the biosphere are maintained within a fixed range.

How Do Humans Affect the Oxygen Cycle?

The steady levels of oxygen on earth indicate that human activities do not affect the integrity of the oxygen cycle. This is mainly because it is replenished by photosynthesizing organisms. Also, the activity of decomposers ensures that every molecule of oxygen from plants and animals is returned to the atmosphere. But the levels of gasses like carbon dioxide and nitrous oxide (of which oxygen is a part) are continually rising in the atmosphere due to excessive burning of fossil fuels, manufacturing, and deforestation. These gasses act as a greenhouse for the sun’s ultraviolet radiations, keeping them trapped in the earth's atmosphere. This greenhouse effect is contributing to a rise in the earth’s temperature and related climate changes.

The Nitrogen Cycle

Nitrogen is the most abundant element in the atmosphere which constitutes 78% of the air around us (NASA Global Climate Change, 2016). This incredibly high amount of nitrogen is sufficient to explain its vitality for the sustenance of life on earth. The soil that we grow our food in, the air we breathe, and the water we drink all contain nitrogen. These nitrogen reservoirs are not static; nitrogen continuously flows from one source to another.

This cycle begins with the fixation of atmospheric nitrogen into the soil. This is done via two methods. One is the atmospheric fixation that occurs during the lightning process. Precipitation brings this nitrogen down in the dissolved form. The second kind of fixation is done by nitrogen-fixing bacteria. Some of the nitrogen is also fixed into ammonia by chemical industries.

Once in the soil, the nitrification of nitrogen starts. Again, this occurs in a number of ways. Firstly, ammonia is converted into nitrites by *Nitrosomonas* bacteria. These nitrates are further converted to nitrates by *Nitrobacter*. Accumulation of nitrates in the soil improves its fertility.

Nitrogen enters the food web in the form of nitrates. These nitrates are taken up by plant roots and assimilated into structural and functional plant proteins. Animals consume these plants to access nitrogen.

The process of returning nitrogen back into the atmosphere operates in the form of ammonification and denitrification. The decomposition of dead plants and bacteria converts their nitrogen into ammonia. Lastly, the anaerobic denitrifying bacteria process nitrates to release nitrogen gas back into the atmosphere.

How Do Humans Affect The Nitrogen Cycle?

Balancing the amount of nitrogen between water, soil, and living things is the key here. Any form of irregularity here can lead to undesirable consequences. Unfortunately, activities like fossil fuel burning and N-fertilizer application increase the amount of nitrogen on land and in the water. Exploitative agricultural practices are causing the leaching of nitrogen out of the soil and into the water bodies. In the water, this nitrogen is promoting eutrophication and dead-zone formation. To overcome the nitrogen deficiency in the soil, farmers are resorting to nitrogen fertilizers which may improve soil fertility briefly but, in the long run, have negative ecological effects. Nitrogen leaches calcium and magnesium from the soil, which affects the soil's fertility. Furthermore, an excessive amount of nitrogen oxide particles in the air is creating respiratory health issues. These and several other issues are created solely because of anthropogenic interference with the nitrogen cycle.

The Phosphorus Cycle

Phosphorus is a vital part of several important biomolecules. It is found in energy molecules like ATP, ADP, and NADP. Structural and functional molecules like nucleic acids and phospholipids contain phosphorus too. On land, phosphorus exists in combination with calcium, iron, and aluminum. These combinations are rather stable, making phosphorus not actively available for plants. Through a chain of chemical conversions, however, phosphorus is then made available to the plants.

Plants use phosphorus in the form of triphosphates. This form of phosphorus is taken up by plants and used for metabolic purposes. From there, phosphorus is accumulated by animals and humans where it acts as an important constituent for bones and teeth. When these animals and plants die, the decomposers return organic phosphorus back into the atmosphere. A substantial amount of phosphorus from the phosphorus cycle is lost to sedimentation that occurs in water bodies. Phosphorus that becomes part of teeth and bones also remains absent from the cycle for a long time.

How Do Humans Affect the Phosphorus Cycle?

Humans are interrupting the flow of the phosphorus cycle through mining and agricultural practices. Mined phosphorus is used in the production of animal feeds, fertilizers, and detergents. In any case, this phosphorus is released into the soil or water. The excess phosphorus that enters the soil is gradually accumulated since it is an inorganic form and there is no active mechanism to turn it into an organic form. This affects the quality of drinking water. The fraction that enters the water bodies is known to cause eutrophication (accumulation of minerals and nutrients which results in the excessive growth of algae and other plants on water). Eutrophication threatens the survival of aquatic life, especially in freshwater ecosystems.

The Sulfur Cycle

Sulfur is an important part of living systems. In animals, it exists mainly in the form of proteins while in plants it is involved in the production of protein, chlorophyll, and waxes. Sulfur is usable for plants when it is in the inorganic sulfate form. Plants uptake these sulfates from the soil solution and use them for protein synthesis. Consumption of these plant proteins transfers this sulfur to animals. Here again, the decomposers play their role by decomposing dead plants and animals to return sulfur to the soil. Aerobic decomposers do so in the form of sulfates, but anaerobic bacteria produce sulfides. Sulfides are then converted to sulfates by sulfur bacteria. This sulfur is either taken up by the plants again or is sedimented in the water bodies.

In the atmosphere, sulfur is present in the form of sulfur dioxide. Volcanic eruptions, sea spray, fossil fuel combustion, and industrial manufacturing are the greatest sources of sulfur dioxide which stays in the air until it combines with rain and comes down as sulfuric acid.

How Do Humans Affect The Sulfur Cycle?

Human activities have disturbed the balance of the sulfur cycle by increasing the percentage of atmospheric sulfur. This has been an aggravating problem since the industrial revolution. Excessive burning of fossil fuel releases hydrogen sulfide and sulfur dioxide into the atmosphere. The rain that falls in the presence of these gasses is highly acidic, which lowers the pH of soil and water alike. Soil productivity decreases, and the survival of aquatic life is put at stake.

Misunderstandings of Carbon

Have you ever wondered what is wrong with the element carbon? Why are its rising levels considered an ominous sign for the earth when carbon is the most important constituent of life on earth? The earth's surface itself has 650,000,000 Gigatonnes of Carbon (GtC) stores while the atmosphere has a 3.2 GtC yearly influx (Green & Byrne, 2004). Plants and animals also use carbon as their structural and functional element. These carbon stores are not permanent; nature has an elaborate system that continuously juggles carbon between the earth, living organisms, and the atmosphere.

- The carbon stored on land consists of slowly-changing reserves, which means that it takes hundreds of years for this carbon to leave its reserve to enter the atmosphere. About 80% of this carbon exists in rocks and sediments (*Carbon Cycle*, 2022). The rest of it exists as kerogens (dead plants and animal sedimentation deep into the ground). Naturally, this carbon remains dormant for several thousands of years and is released into the atmosphere in small amounts through the metamorphism of limestone or volcanic eruptions.

- In the oceans, carbon is cycled between two layers. The upper layer rapidly exchanges carbon with the atmosphere in the form of dissolved inorganic carbon while the lower layer does this at a slower pace (in a matter of hundreds of years) mainly because it takes a lot of time for this carbon to reach the upper layer. The entry of carbon into the oceans occurs in two forms: dissolved carbon dioxide or dissolved organic carbon. From here, it is either used by photosynthetic organisms or turned into sediment for storage in the lower ocean layer.
- Terrestrial carbon includes the carbon present in plants and animals (both living and dead) plus the amount in the soil. Atmospheric carbon enters the living systems through autotrophs which convert it to an organic form. Heterotrophs use autotrophs to obtain carbon. In living systems, carbon constitutes the basic chain of all organic molecules including DNA, RNA, carbohydrates, proteins, and lipids. As far as the carbon's return back into the atmosphere or ocean is concerned, it is done primarily through respiration. This not only includes animal respiration but soil respiration (by soil organisms) too, while some of it goes into the oceans in a dissolved organic form.

This means that there is nothing wrong with the carbon itself—it is well-regulated in the closed system of the biosphere. So, where is this "carbon problem" arising from? Just as with other cycles, it is the anthropogenic effects that disturb the balance of the carbon cycle. Let's see how:

- Activities like fossil fuel extraction and burning add carbon dioxide into the atmosphere directly from the geosphere.
- Mining of limestone and its processing into cement releases a large amount of carbon into the air.
- Modification of the land mainly for agriculture severely affects the ecosystem's ability to withstand environmental stress and act as a carbon sink. The same has happened in the last century in several parts of the world.
- Sunlight-induced degradation of plastic produces carbon dioxide and other greenhouse gasses. This may not be a big issue currently, but it will be one in the coming years.
- High populations of herbivores are being seen as a problem for the carbon cycle mainly because selective eating of high-quality green plants and trampling of grasses is decreasing the carbon-sinking capacity of plants. The compaction of soil is decreasing its carbon dioxide-holding capacity.
- Lastly, the carbon-holding capacity of the oceans is decreasing, contributing to their acidification. Ocean acidification can have dramatic effects on the activity of sensitive aquatic ecosystems like coral reefs. Coral reefs can store 70–90 megatons of carbon in their calcium carbonate skeleton, but ocean acidification is gradually destroying these coral reefs (Kault et al., 2022). This lowering pH is negatively affecting the shell-forming capacity of mollusks too.

All of these events show that anthropogenic activities increase the amount of carbon in the atmosphere while also decreasing the capacity of carbon sinks. Before the industrial revolution, the levels of carbon dioxide in the atmosphere were 280 ppm (National Oceanic and Atmospheric Administration, 2022). Since then this amount has increased rapidly and now measures 415.41 ppm (Daily CO2, n.d.).

These rising levels of CO2 are proving disastrous for land, water, and living organisms. The soils are reacting rapidly to these levels. Not only the input but the release of carbon from the soil has increased. The main reason for this increase is the elevated global temperature, which increases the activity of all soil organisms including aerobic bacteria. For oceans, rising CO2 levels mean an increase to the acidification of water. A drop in pH affects the shell-forming capacity of marine organisms.

Last, the biggest problem is the greenhouse effect caused by CO2 and other harmful gasses. The greenhouse effect is trapping excessive heat from the sun and turning the world into a self-imploding entity. Glaciers are melting, ocean levels are rising, animal and plant species are being endangered due to the destruction of their habitats, food production is decreasing, new diseases are emerging, and land is turning inhabitable for humans and animals.

It's not the carbon cycle that is flawed, it's our fatal strategy and unsustainable lifestyle.

Photosynthesis

Let us look at the process that is responsible for primarily producing energy within the food web: photosynthesis. This is the process through which plants, algae, and bacteria generate energy using light, water, and carbon dioxide. This process not only creates energy that drives the whole food web but also creates an ecological balance by reusing carbon dioxide and releasing oxygen into the system. This process acts as a reliable sink for carbon while maintaining a healthy oxygen cover on the biosphere. The products of photosynthesis are not only important for the plant itself but for other living organisms too. The energy from plants is transferred to animals (herbivores) and humans where it is used to construct their proteins, carbs, and lipid molecules. The sucrose solution produced during photosynthesis is fed to the soil organisms too (via their roots). Oxygen produced during photosynthesis is crucial too. It is used by both humans and animals for respiration. Aerobic bacteria, on the other hand, use oxygen to decompose organic matter.

The green-colored chlorophyll in plants effectively captures light energy (of the required wavelength) for photosynthesis. The carbon dioxide required for the entire process is captured via small pores (stomata) that are present on the surface of leaves while water is acquired from the soil via plant roots. Water and oxygen produced as a by-product of photosynthesis release into the atmosphere through stomata. Photosynthesis begins once all of the required ingredients have assembled in the aerial parts of the plant. The light energy expels electrons from water molecules which are then used to reduce carbon dioxide until carbohydrates generate. In the case of anoxygenic photosynthesis, sources other than water are used to acquire these electrons and no oxygen is produced as a by-product.

For ease of understanding, biologists divide photosynthesis into two processes: namely, light reaction and dark reaction (also known as the Calvin cycle).

Light Reaction

As soon as the light hits the chlorophyll molecules, an electron is released. This electron then moves through a chain of protein complexes to collect sufficient energy for the generation of ATP and NADPH. The hole created in chlorophyll by the loss of an electron is filled up by another electron from water. Oxygen produced from water breakdown is released into the atmosphere.

Dark Reaction

In the dark reaction, ATP and NADPH are utilized to create sugar for plants. An enzyme called rubisco incorporates carbon dioxide into 3-phosphoglyceric acid (3-PGA).

In this process, ATP is utilized. 3-PGA is then reduced using NADPH molecules into two molecules of glyceraldehyde 3-phosphate (G3P). One of these G3P molecules is then used to recreate rubisco and sugar molecules.

Types of Photosynthesis

Based on the carbon intermediate used, photosynthesis divides into three types; C3, C4, and CAM.

- C3 photosynthesis is the most common type. In the Calvin cycle of this type, the carbon intermediate used is 3-PGA.
- The C4 type that occurs in sugarcane and maize utilizes a four-carbon intermediate, oxaloacetate, as the starting material. Oxaloacetate is further broken down into malate. Malate releases carbon dioxide which is then used for the formation of rubisco and carbohydrates. C4 photosynthesis is better suited to hot and dry environments where it is too risky for plants to open their stomata for the most part of the day.
- Crassulacean acid metabolism (CAM)-based photosynthesis is for desert plants that open their stomata only during the night for gaseous exchange. The carbon dioxide that enters plant leaves during the night fixates into oxaloacetate and then into malate or any other organic acid. This carbon dioxide is further available to the plant during the day for light reaction.

Photosynthesis Links Them all Together!

By now, you probably realize how all of the mineral cycles are linked together through photosynthesis. It actively cycles carbon, water, and nitrogen. Other minerals like phosphorus and sulfur are involved too.

- Plants, being a major sink of carbon, take up huge amounts of carbon dioxide via their stomata and use it as a starting material for photosynthesis. Because of this, inorganic carbon is converted to organic form to be passed on to the next tier of the food web.
- Water is not only used as a starting product but also released as a by-product of the process. In fact, it is the transpirational loss of the water itself that creates a pulling force for the influx of water via plant roots.
- DNA and RNA and protein molecules that direct the execution of photosynthesis contain nitrogen. The basic structure of chlorophyll molecules also contains nitrogen molecules. This nitrogen is absorbed via the plant roots.
- The carbon intermediaries used during the Calvin cycle contain phosphorus atoms.

3

SOIL BIODIVERSITY AND THE SOIL FOOD WEB

We have discussed the mineral components of soil and how their cycling works between soil, atmosphere, and living organisms. Each of these elements play a crucial role in the life cycle of plants and animals and also in maintaining a balance within ecosystems. But what about the soil organisms? How are they involved in the maintenance of healthy soil and in the cycling of nutrients between different parts of the biosphere? And how do these soil organisms maintain the health status of plants? These are the questions that need to be answered; because we cannot talk about plant health while ignoring millions of bacteria and hundreds of fungi, protozoa, nematodes, and microarthropods found in every gram of soil.

The work of Dr. Elaine Ingham is very insightful in this regard. As a microbiologist, she has done extensive research on the relationship between the soil food web and its influences on plant health. She has presented her research in the form of a soil food web health management (SFWHM) system, according to which soil with elaborate food webs is the best suited for plants. However, such soil food webs evolve over a long period of time and our current agricultural practices are continually damaging the integrity of these webs. To restore these food webs and regenerate soil, she has proposed a three-tier plan that involves the isolation and identification of missing soil organisms, their reintroduction into the soil, and the adoption of biologically safe farming practices.

What is the Soil Food Web?

Merriam-Webster defines the food web as “the totality of interacting food chains in an ecological community.” Simplistic food chains are commonly known where one organism transfers its energy periodically to a number of other organisms in a hierarchical order. The combination of multiple food chains interacting with each other generates a complex diagram known as food webs.

Recall your school biology lectures where you might have studied that living organisms interact with each other at several levels, one interaction being the basis of food and nutrient acquisition. These interactions are what make up a food web. But at that time, you would have only studied food webs involving terrestrial animals and humans. By now, you’ve probably guessed it—the same kind of food web exists within soil organisms. You’d think that this food web might not be as complex as the terrestrial food web, but it is in fact several times more complex than that.

Importance of Soil Food Web

The soil food web involves all of the living organisms that live entirely or part of their life in soil while interacting with plants. There is a lot more to these soil–plant interactions than meets the eye. These organisms interact with each other and with plants not only to exchange energy (in the form of nutrients), they protect the plants against disease and stress too. Regarding nutrient availability, these organisms break down the organic matter to release individual minerals into the soil that are then taken up by the plant roots. Maintaining soil health by improving its structure and nutrient profile protects the plants against stresses (like drought and flood) and diseases. For farmers, a healthy soil biome could mean more productive soils, good soil structure with high moisture content, and crops with a natural resistance to disease and stress.

Unfortunately, human interventions have caused severe disruptions in the nutrient cycles and in the soil structure. To deal with the resulting soil problems, they have resorted to fertilizers, pesticides, herbicides, and tilling. These chemical and environmental stresses have severely damaged the soil biome. The absence of nutrients and suitable soil structure has removed several organisms completely from the soil and the remaining ones are suffering due to these missing links from the food web.

In short, disruptions in the soil food web has a plethora of direct and indirect consequences:

- Soil productivity is decreased.
- Agricultural soils demand more fertilizers and chemical additives thus increasing the cost of production.
- Rampant use of chemical fertilizers has disastrous environmental impacts.
- Soil erodes and sediments in the water bodies.
- There is an increase in droughts and floods.
- More crops are infected with diseases.
- Weeds and pests are common.
- The exclusion of some organisms from the food web is putting the whole of biodiversity at risk.

Trophic Levels of Soil and What Resides at Each Level?

The population of soil is so diverse and large that, until now, we have only identified and studied a very small fraction of them. So, naturally, we are not aware of the exact function that each of these organisms performs or how it interacts with others. To deal with this, biologists have divided organisms on the basis of their function or their interaction with other organisms. Therefore, organisms involved in food webs are grouped together into levels called “trophic levels.” A trophic level refers to the parts of an ecosystem at which a particular organism resides and feeds on other organisms. Since the soil food web is one of the most complex ones, it is studied under five distinct trophic levels.

First Trophic Level

This level provides a base for the whole food web as it contains most of the photosynthetic organisms. These organisms obtain energy directly from the sunlight, carbon dioxide from the atmosphere, and water from the soil itself to generate food for themselves and several other organisms that reside in trophic levels below this one. These photosynthetic organisms include trees, plants, herbs, shrubs, lichens, mosses, ferns, fungi, and photosynthetic bacteria.

Dead plants and animals, plant leaves, fruit drop, crop residues, and other organic wastes (like dung, bird droppings, and kitchen waste) also exist on this level. This is also the level at which organic matter begins to form. The breakdown of organic residues into simpler matter provides easy nutrient access to the organisms residing at the second trophic level.

Second Trophic Level

This is the level at which the consumption of nutrients finally begins. But unlike the terrestrial ecosystems, this consumption is done at simpler levels. The organisms found here are simple microscopic entities that decompose organic matter and consume nutrients from it. Bacteria decompose dead plants and animals into simpler forms, while herbivores and plant parasites derive energy by feeding on living plant tissues. There are some microbes that rely solely on root exudates.

Third Trophic Level

This level contains nematodes and microarthropods which shred plants and other organic matter into tiny pieces before consuming it. Such organisms are called shredders. Predators, like some nematodes and protozoa, feed on other fungi and bacteria. Some types of protozoa graze on organic matter too. Organisms at this level play a crucial role in breaking organic matter into smaller pieces which facilitate their decomposition by bacteria. Grazers help in mixing the organic matter well with the soil.

Fourth Trophic Level

This trophic level is all about predation. Large predatory arthropods and nematodes are the organisms found abundantly on this level. They feed on the organisms found in the third trophic level. Garden wasps and beetles are also present here.

Fifth Trophic Level

The fifth trophic level is composed of higher-level predators that feed on the fourth-level organisms. This includes birds and mammals. Some beetles and predatory mites feed at this level too.

Organisms at each trophic level are dependent on the trophic level below it for energy. It may seem that species at the same trophic level are functionally the same but that's not true. Their overall impact on the other trophic levels may be the same but each individual organism at each level has its own vitality, and any change in the number or the location of that species has the potential to throw the entire system off balance.

How Does the Food Web Affect Plant Health?

The consumption of organic matter that begins at the second trophic level and continues till the fifth trophic level of the soil food web benefits plants the most. Decomposers release digestive enzymes to dissolve the organic matter into freely available molecules. Only a small portion of these nutrients is used up by them to derive energy for growth and reproduction. The rest of them are left for the plant roots to absorb. Shredders and grazers help by breaking down the organic residues into smaller pieces and then mixing them well with the soil. Since most of this activity takes place near the plant roots, plants face no hurdles in accessing these nutrients. High-level activity near roots also provides a feeding ground for predators that feed on root pests, thus eliminating the need for chemical pesticides. Plant roots produce exudates on which symbiotic bacteria feed and, in return, help the plant get rid of plant diseases. Recycling the nutrients back to plants mobilizes mineral cycles and restarts the feeding cycle once again.

Imagine for a moment that we remove all of the *Nitrobacter* bacteria from the soil food web. What will happen and how will that impact the balance of the ecosystem? Initially, the system will operate normally. Soil nitrogen present in the plant-available form will be taken readily by the plants where it will be used to synthesize plant protein and other vital enzymes. Animals and humans will consume a part of this nitrogen via their diet.

Application of nitrogen fertilizers and lightning will slowly return nitrogen back to the soil. Nitrogen fixers will play their part too. Nitrosomonas will convert this nitrogen into nitrites. But, due to the absence of *Nitrobacter*, the nitrogen cycle will come to a standstill. Nitrogen will gradually accumulate in the soil, but since nitrates will no longer be present, the rate of photosynthesis and overall growth of plants will suffer. This, ultimately, will affect the integrity of both terrestrial and soil food webs.

Functions That Soil Organisms Perform

The importance of the soil biome for the sustenance of healthy plant growth has been discussed in detail, but the function of this biome is not limited to the soil. There are a number of other functions that soils perform to maintain a balance between different components of the ecosystem. Let's have a look at these functions.

Decomposition

This is the function that is designated solely to the soil organisms. Decomposition occurs in a number of steps where shredders and grazers break up larger matter into smaller pieces before the decomposers come into action and degrade it to release the constituting nutrients. This re-enters them into the food web.

It is, in fact, the decomposition process that provides the incentive for other functions of soil organisms including hydrological cycling, nutrient cycling, and pollution control. Decomposition occurs in the following steps:

1. Fragmentation—the breakdown of detritus into smaller pieces to increase its surface area of microbial attacks and to mix well within the soil.
2. Leaching—the process by which inorganic minerals separate from organic matter by dissolving in water and leaching out.
3. Catabolism—the conversion of broken-down organic matter into inorganic compounds via bacterial and fungal enzymatic action.
4. Humification—the formation of the dark, nutrient-rich soil layer that is resistant to microbial attacks and contributes greatly to soil fertility.
5. Mineralization—the release of inorganic nutrients from humus into the soil.

Factors like residue quality, temperature, moisture, pH, and aeration have a profound effect on the rate and efficiency of decomposition.

Nutrient Cycling

Soil organisms constitute a crucial link in all of the major nutrient cycling systems. In the soil, this nutrient cycling works in the form of nutrient breakage and nutrient assimilation. While some of the nutrients are released directly into the soil via decomposition, some of them are released when predators like nematodes consume bacteria and fungi, digest them, and release nutrients via their fecal matter. Both of these actions create an abundance of nutrients for plant growth, thus eliminating the need for chemical fertilizers.

Nutrient and Water Retention

The characteristic of soil nutrient retention is also due to soil organisms. Bacteria and fungi help in nutrient retention by fortifying soil particles. This reduces nutrient leaching from the soil. However, current agricultural practices are damaging the nutrient retention capacity of the soil by damaging soil microbes and destroying the natural structure of the soil. Soil organisms are also necessary for increasing the water retention capacity of the soil. Soil with rich biodiversity has high OM and therefore more water-retaining capacity.

Bioturbation

Bioturbation refers to the movement of soil organisms within the soil structure that causes mixing of soil as well as creates small channels in it. Grazers and shredders are the main characters of bioturbation. The churning of soil constituents not only changes the physical properties of soil but also impacts the chemistry of soil ecology. Bioturbation is thought as a major force behind the vertical mixing of soils (Aquino et al., 2017). This vertical mixing allows soils to change overtime. The organic matter collecting on the top is taken in and mixed well with all soil layers.

Bioturbation creates sufficient spaces between soil aggregates to allow for an active exchange of gasses and water molecules. Nitrogen, carbon dioxide, and hydrogen sulfide are some of the gasses produced during decomposition and need to be released continuously in the air.

Disease Suppression

The diversity of soil microorganisms acts as a biocontrol agent by dealing with plant and human disease-causing pathogens through a variety of strategies.

In addition to the soil organisms, there is also a huge population of microbes that can infect humans, plants, and animals. But in order for them to spread disease, they must first establish themselves in the soil (especially if they are not resident species). Besides, some of these microbes require a carrier to transmit the disease to the targeted animal or plant. There are several kinds of interactions going on within soil communities where they compete for access to resources. Soil organisms control the activity of pathogenic microbes by limiting their access to these resources.

In the sea of soil microbes, the pathogenic species remain suppressed for several years, and even when they thrive, they have to wait for a carrier. In most cases, competitions like parasitism and commensalism are sufficient to finish them off. Other than soil microbes, other organisms also play an important role in keeping pathogenic bacteria under check. For instance, dung beetles are known to remove *E. coli* from freshly-tilled farms by ingesting *E. coli* containing feces and burying them deep into the soil where they are controlled by other antagonistic soil communities (Jones et al., 2019). Chemical features of soil such as moisture content and pH also help to prevent the growth of pathogenic microbes.

Toxin Decomposition

As an active part of nature's bioremediation process, the soil organisms detoxify several toxins that are released into the soil via agricultural applications or industrial effluents. Adsorption, precipitation, volatilization, chemical detoxification, and biological immobilization are some of the pathways employed for toxin detoxification in the soil. These processes have been found to be most efficient in the top 39 inches of soil ("Soil - Pathways of Detoxification," 2019).

The energy acquisition process in bacteria involves transferring electrons from organic matter to electron-accepting species. When toxins are present, bacteria preferentially use them for electron transfer. On accepting the electron, these toxins are chemically modified and so their toxicity is reduced.

Many types of fungi are known to perform "mycoremediation" by capturing soil toxins and chemically processing them until they are completely detoxified.

Soil Structure Building

Both mineral constituents and living organisms of soil have a profound impact on soil structure. Initially, the type of soil, pore sizes, and available nutrients create a diversity of microclimates for different soil organisms to grow and interact. Once the soil organisms reach a certain level, their activities and metabolite production starts to affect soil structure and chemistry. OM in general acts as a sponge with a superior water-absorbing capacity, which is then released according to the soil's water requirements. Fecal matter produced by soil organisms has high nutrient and moisture retention too.

The aggregating solutes (like glycoproteins) produced by soil organisms hold the soil particles together as macroaggregates and thus help in soil structure formation. Bacteria form special biofilms around soil aggregates, while the network formed by plant roots and fungi binds larger aggregates together. Plant roots provide strong structural fortification as they grow and abundantly entangle with each other and with soil aggregates. Lastly, bioturbation by grazers and shredders creates new pores between soil particles and helps create new soil aggregates. Soil structure formed this way lowers the chances of soil erosion and improves infiltration rates while strongly holding onto soil nutrients.

Who Rules the Web?

The importance of microorganisms in the soil can never be overstated. Not only are they the most important contributors of biomass in the soil but are also involved in executing important soil-related functions. They determine plant health, recycle nutrients, maintain a balanced ecosystem, and much more. Considering the biodiversity and population of microorganisms in the soil, you'd think that these are the ones that are ruling the soil food web, but that's not true!

Even after what microorganisms do for soil, they aren't the controllers. Their growth and diversity are commanded by plants. But that's good! This allows the plants to decide which kind of bacteria and fungi that they want (or need) in their vicinity.

Plants do so by releasing a special kind of exudate from their roots to attract specific bacteria and fungi to their rhizosphere (soil that is in direct contact with roots). These exudates are mainly composed of sugars but may also contain protein and other carbohydrates. The composition of these exudates varies for each kind of bacteria or fungi that a plant wants to attract. Bacteria and fungi belonging to different species perform different functions for the plant. These microorganisms produce enzymes that help extract specific nutrients from the soil and make them available to the plants. Nematodes and arthropods feed on some of these bacteria and fungi and release these nutrients ready for root uptake.

Microorganisms that reside in the rhizosphere of a plant are not active all the time. They reside in a state of inactivity only to be activated when required. For instance, if a plant is facing salt stress, it'll require more potassium to regulate its osmotic balance (Hasanuzzaman et al., 2018). To upregulate the activity of potassium, the plant roots will produce a specific exudate that'll in turn activate bacteria and fungi associated with potassium accumulation. These bacteria and fungi will squeeze out potassium from the organic matter and convert it into plant-accessible form for easy uptake.

The production of exudates is a lot more complex than it seems. Dr. Elaine Ingham likes to explain this complexity by comparing exudate production with cooking. According to her, if during cooking, we want to sweeten something, we choose from a range of options: cane sugar, brown sugar, honey, molasses, and agave are all viable options. The same happens for exudate production—the plant selects which sugar to put out through exudate based on the microorganisms that it wants to attract. Once the microorganisms perform their specific functions, the release of exudates slows down and microorganisms are pushed into a state of dormancy until required again.

Understanding Rhizophagy

Rhizophagy is the term that refers to the complex set of interactions between soil and its microbes (in the rhizosphere region of a plant). These interactions can have profound effects on nutrient availability for plants. The rhizophagy cycle determines how plants access macronutrients (like nitrogen, phosphorus, and potassium) and micronutrients. To ensure the availability of nutrients, plants "farm" the required microbes in a methodical manner unless disturbed by abiotic factors. This microbe farming is done through the production of root exudates, as discussed earlier.

Before the discovery of this "rhizophagy cycle," biologists thought \that root hairs only had nutrient access in the form of dissolved mineral ions. However, this cycle discovery has shifted the focus from dissolved nutrients to microbes. Now we know how roots can suck nutrients directly from the soil microbes.

As part of this process, plant root tips (having young root hair) engulf bacteria and fungi which contain the required nutrient. Once in the roots, superoxides that oxidize the cell walls of these microorganisms release the nutrient directly into the plant root. The plant instantly starts the nutrient transport before it diffuses out again. Microbial constituents diffuse out where they reassemble a cell wall and return to their normal working ground. According to the details provided by White et al. (2018), rhizophagy cycle involves the following twelve steps:

1. The process begins with the production of exudates with unique compositions to attract specific bacteria and fungi to the rhizosphere. Feeding on the exudates, the microbe population grows rapidly.
2. Microbes start growing in between the cell wall and plasma membrane of plant root cells.

3. Superoxide is produced by root cells, which oxidizes the microbial cell walls.
4. The continuous movement of the microbe protoplasts (cell components) within the root cells extracts nutrients from microbe protoplasts.
5. Within the root cells, microbe protoplasts are copied several times to generate a huge population.
6. These protoplasts stimulate root hair formation for future rhizophagy cycles.
7. Microbe protoplasts are ejected back into the soil.
8. Root hairs secrete exudates onto recently ejected microbial components.
9. This provides sufficient energy for protoplasts to reassemble cell walls around them, thus reforming the microbial cell.
10. These microbes start colonizing the plant rhizosphere.
11. Once established, they start acquiring more nutrients from the soil (for themselves and the plants).
12. The cycle begins again with the rhizosphere colonization of microbes.

The efficiency of the rhizophagy cycle is dependent upon the production of peroxides. The more peroxides a plant root produces, the easier it is to break the cell wall and release the nutrients. The frequency of nutrient cycling also depends on the number of root tips because they are the sites for exudate secretion and also of microbe internalization.

Macronutrients

On the basis of quantities required, plant nutrients are divided into two distinct categories. The macronutrients category includes the nutrients nitrogen, potassium, phosphorus, calcium, magnesium, and sulfur. The first three are collectively known as NPK, and they are the most important ones. Let’s look at some of the functions of these macronutrients and how their deficiency can impact the well-being of the plant.

Nitrogen

Nitrogen is the most important soil nutrient that ensures plant growth. This doesn’t simply mean longitudinal growth of plant stems, this means the healthy growth of plant roots, stems, leaves, and fruit. Nitrogen controls plant growth by controlling the execution of photosynthesis. Together with magnesium, nitrogen forms the central structure of chlorophyll molecules. Nitrogen is an essential component of all plant proteins and enzymes. Nitrogen is required both during the vegetative as well as reproductive part of plant life.

Both the deficiency and excess of nitrogen are harmful to plant health. Its deficiency leads to poor plant growth while its excess causes delayed flowering/fruiting and abnormal cell growth.

Phosphorus

Phosphorus is the “plant growth” nutrient that sequesters energy from the sunlight to kick-start photosynthesis. It is involved in stimulating root and shoot meristems as well as in the ripening of fruits and germination of seeds. Phosphorus is the structural component of vital plant structures. For one, it forms the hereditary structures of DNA and RNA. Plant fats and waxes are composed of phospholipids of which phosphorus is an essential part. These phospholipids are also present abundantly in plasma membranes, where they assist in moving molecules in and out of the plant cell. ATP, which is the basic energy-rich molecule for driving most biochemical reactions, contains phosphorus as an integral part. In fact, it is the bond breakage between phosphorus molecules that releases energy from ATP (converting it to ADP). Phosphorylation, which is a basic chemical reaction type, includes the addition of phosphorus to different enzymes and molecules to modify them structurally and functionally. Phosphorylation reactions are involved in several forms of cell signaling pathways in plants. Phosphorus also promotes water-use efficiency in plants, especially in drought-affected areas.

Low pH and dry soils can induce a phosphorus deficiency in plants visible in the form of dark green or purple-edged leaves, early vegetative stage, and early ripening of fruits. Cold temperature, pest infestation, excessive herbicide application, and soil compaction can also trigger phosphorous deficiency symptoms.

Potassium

Potassium executes several metabolic functions. It does so by maintaining the structural and functional integrity of several plant parts. For instance, it helps to regulate the opening and closing of stomata. Opening of stomata allows for gaseous exchange and transpiration.

A special type of “potassium ion pump” regulates the turgidity of stomatal guard cells thereby opening them for gaseous exchange and then closing them to prevent excessive water loss. Potassium ion pumps play a huge role in sustaining plants during water scarcity (and droughts). Potassium also

- activates several enzymes involved in the plant’s primary metabolism (photosynthesis and respiration).
- regulates carbohydrate and protein synthesis.
- assists enzymatic activity.
- assists photosynthesis especially when light intensity is low.
- assists in cellulose synthesis.
- helps in plant cell signaling and cell growth as well as aids in sucrose transport.
- induces tolerance against a number of biotic and abiotic stresses like cold, salinity, pests, and diseases (Wang et al., 2013).

Plants facing potassium deficiency are prone to infections. They are easily distinguishable by leaf coloration and texture. Due to the loss of turgidity and excessive water loss, leaves appear flaccid and yellowish in color.

Calcium

Calcium is the plant’s construction engineer. In several parts of the plant, it helps construct new structures. Leaves contain high concentrations of calcium, which provide structural rigidity in combination with other organic compounds. Roots are also rich in calcium stores where calcium assists in root hair formation. Calcium plays a vital role in cell wall formation and therefore it is rich in roots. Calcium develops plant shoot meristems where rapid cell growth and differentiation occur. Calcium assists in nitrogen absorption and neutralization of acids both on and in the soil.

Generally, soils are rich in calcium because of the presence of lime, dolomite, and gypsum as parent materials, all of which are calcium-rich rocks. But soil that does lack calcium often shows stunted plant growth. Root systems take the greatest hit because calcium deficiency interrupts root elongation and root hair formation.

Magnesium

Along with phosphorus, magnesium forms the basic structure of chlorophyll molecules, plus it acts as a cofactor and electron carrier for several enzymatic reactions. This makes it extremely vital for all photosynthetic plants.

Magnesium deficiency mainly occurs because of leaching, which typically happens due to soil acidity and excessive rainfall. Excessive application of potassium fertilizers can also cause magnesium deficiency.

Sulfur

Sulfur is an aroma-inducing nutrient for plants. The strong smell of garlic, onion, and cruciferous vegetables is due to sulfur. It is also an essential part of some proteins. The uptake of nitrates from soil and their conversion into proteins involves sulfur at several points. The electron transport chains of photosynthesis contain sulfur too.

Sulfur leaches out rapidly from the soil but is quickly replenished through seaspray (in the coastal areas), organic matter, and ammonium sulfate fertilizers.

Micronutrients

Micronutrients or trace nutrients are needed by plants in small quantities to ensure the smooth execution of the processes where they are required.

Iron

Iron constitutes various enzyme cofactors in plants. It also helps in the structural formulation of chlorophyll and DNA. The efficiency of nitrogen fixation and respiration is dependent on iron.

Zinc

Zinc is involved in the production of the growth hormone auxin which causes stem elongation and leaf expansion. Ethylene, which causes the ripening of fruits, also requires small amounts of zinc. The efficient cycling of oxygen, hydrogen, carbon, nitrogen, and sulfur requires zinc. A deficiency of zinc causes stunted leaf and stem growth.

Copper

The enzymes involved in photosynthesis and lignification of plant cell walls contain copper. Soils deficient in copper lead to poor plant growth with yellowing of leaves (chlorosis) due to a reduction in the rate of photosynthesis.

Boron

Boron is actively involved in all the processes that involve rapid cell differentiation and cell growth. Therefore, it is important for plant growth, pollen germination, flowering, and fruiting. It is involved in the adsorption and metabolism of calcium. It assists in the metabolism of large biomolecules by facilitating their movement through cell membranes.

Manganese

Manganese facilitates photosynthesis by causing the hydrolysis of water molecules. It also causes the activation of certain enzymes. The immunological strength and stress tolerance of plants is also boosted due to manganese. Waterlogging and excessive tilling lower manganese in the soil.

Molybdenum

Molybdenum is not directly involved in the plant's primary metabolism but it is involved in promoting nitrogen metabolism at several stages. First, it promotes nitrogen fixation by up-regulating the activity of the nitrogenase enzyme. Then, it regulates the nitrogenase reductase enzyme to reduce nitrates to nitrogen gas. Besides these reactions, the formulation of amino acids and proteins is also managed by molybdenum.

Chloride

Chloride is the ionic form of chlorine with a negative charge. It is required in very small quantities to regulate osmosis. Osmosis is the movement of dissolved solutes (ions) from one solution to another. Chloride ions are also implicated in the execution of light and dark reactions of photosynthesis.

Silicon

Silicon is present in several plant structures, and even though the exact function of silicon in plants is not fully understood, it is often associated with improved resistance to biotic and abiotic stresses like cold temperatures, drought, pests, and diseases. Silicon also contributes to an overall increase in plant biomass and yield.

Nickel

The exact role that nickel has in plants is not fully understood; however, small amounts are vital for plants because it processes urea during nitrogen metabolism. A deficiency of nickel can cause the accumulation of toxic levels of urea.

Selenium

Selenium is a heavy metal that is known to promote drought resistance in plants. It is also known to help plants grow in highly saline soils. Selenium also protects plants from rapid temperature fluctuation and high-intensity UV radiation.

Cobalt

Cobalt is known to increase the bioavailability of several macronutrients like nitrogen, phosphorus, and potassium. It is also the central component of the most complex vitamin called B12 or cobalamin. It assists in nitrogen fixation and metabolism, especially by promoting the activity of nitrogen-fixing bacteria associated with leguminous plants.

The Four Stages of Plant Health

We have discussed the concept of plant health in detail and how regenerating soil can ensure this health, but the big question is: What do we mean when we say plant health? Or, what is our concept of a healthy plant?

We commonly believe that a plant with access to “living soil” is growing in an abundance of nutrients, and that a high productivity rate is our ideal “healthy plant.” But recently, the concept of plant health has expanded to include several other criteria. This new concept was introduced in 2020 by John Kempf; according to him, regenerating soil not only just achieves physical and chemical health for plants, it also improves their immunological traits, thus rendering them completely resistant to diseases and pests. The taste and shelf life of their yields are also enhanced. These evolving plant traits were noticed after growing in regenerating soils over a number of years. These traits have been attributed to the changing state of the biochemical and physiological processes occurring in plants.

To explain the concept, Kempf developed a four-stage plant health pyramid. The pyramid starts with the two most important requirements that all plants need to meet: photosynthesis and protein synthesis. These two traits depend on the nutritional status of the soil. Most plants are able to complete both photosynthesis and protein synthesis, especially when assisted through foliar applications. Unfortunately, most farmers only aim to achieve these two stages while ignoring the other two tiers of plant health, which, according to Kempf, are increased lipid and secondary metabolite production. These two levels are not as easy to achieve as the first two and can only be achieved through regenerative agricultural practices.

Let's see how successful completion of each of these stages helps to attain greater plant health and which farming practices can help the process.

Complete Photosynthesis

Complete photosynthesis does not only include a rapid completion of light and dark reactions of photosynthesis in a 24-hour photoperiod; it also includes a rapid transition of the produced sugars to carbohydrates. As far as carbohydrate production is concerned, a high proportion of complex-structured carbs and a low amount of non-reducing sugars like sucrose are always preferred. In short, both a quantitative and qualitative increase of photosynthesis is required to complete this stage.

We have started to accept the fact that 20–25% of photosynthesis performed by most plants today is a norm, and that photosynthesis has the potential to increase up to 150–600 times more in the event that the plant attains “complete photosynthesis” status (Advancing Eco Agriculture, 2019). Biologists and soil scientists thought previously that the carbohydrate profile of plants was fixed, but recent findings suggest otherwise. It turns out that this profile can change provided the plant has access to all of the photosynthetically-vital nutrients. Adequate levels of minerals including magnesium, nitrogen, phosphorus, iron, and manganese in the soils can help plants attain the stage of complete photosynthesis.

How Does This Help the Plants?

Kempf observed that successful completion of this stage can help plants gain resistance to a number of soil-borne fungal pathogens. This may be due to the change in the carbohydrate profile of the plant which changes the root exudate composition and ultimately lowers the microbial growth in the rhizosphere.

Complete Protein Synthesis

The second stage is similar to the first one. All that is required of this stage is to process and convert all of the available nitrogen in the plant sap to amino acids and proteins within a 24-hour period cycle (Advancing Eco Agriculture, 2022). This includes nitrogen absorbed from the roots in the form of ammonium nitrate, urea, and amino acids (from OM). Soils rich in magnesium, sulfur, molybdenum, and boron can help in the attainment of nitrogen levels close to zero because all of these elements are involved in nitrogen metabolism both directly and indirectly.

How Does This Help the Plants?

Successful completion of this stage cuts pests at their source (at their food source to be exact). These pests have simple digestive systems that can only digest soluble nitrates present in the plants. They suck these nitrates and use them to synthesize their own proteins.

Therefore, turning all of the soluble nitrates to plant proteins means that there is none left for the pests to feed on. This mechanism is known to effectively deal with several pests like aphids, tomato hornworms, leafhoppers, corn borers, etc. A decrease in the amounts of circulating ammonium also deals with spider mites and thrips.

Increased Lipid Synthesis

The concept of increased lipids synthesis in plants is similar to the fat deposition in humans and animals. Similar to humans and animals who start depositing excess nutrients in the form of body fat, plants start producing fats and oils when there is an energy surplus. But unlike humans, where excess fat deposition can lead to problems, plants benefit exponentially from these oils and fats. Generally, all plants have a baseline level of lipid production that facilitates cell membrane production, although it is insufficient to synthesize any additional oil or wax that could render protection to the plants. In a healthy state, plants can have this lipid production increased to about three to four percent within the dry matter.

For that to happen, plants need to absorb the majority of nutrients from microbial metabolites instead of from the soil. Since nutrients in microbial metabolites are already in the plant-ready form, they save the energy that the plant would otherwise spend on the conversion of nutrients to organic compounds. For example, nitrates that are absorbed from the soil require a major proportion of photosynthetic energy for their conversion to proteins. On the other hand, amino acids absorbed from microbial metabolites do not require any such conversion. This saves photosynthetic energy that can instead be directed toward lipid synthesis.

How Does This Help the Plants?

Regenerative agricultural practices make sure that the indigenous soil microbes remain undisturbed, which results in a larger population. These microbial populations produce extremely high amounts of metabolites that are energy efficient. Plants absorb these metabolites and use their energy to synthesize protective oils and waxes. You must have seen a waxy shine on healthy plant leaves, that’s because of these protective lipids.

Production of these lipids not only increases the oil production in oilseed crops but also boosts plants’ resistance to airborne bacteria and fungal pathogens. A protective waxy layer on plant surfaces resists the action of pectin-degrading enzymes (from pathogens), thus preventing their entry into the plant cells. This could protect the plants from the attack of mildew, rust, blight, and bacterial spots.

Increased Plant Secondary Metabolite (PSM) Synthesis

This stage often begins with the third stage because both these stages involve systemic changes in plant-soil interaction. In this stage, there is a successive rise in plant protective metabolites, which ultimately triggers the immune pathways in the plants. There are two plant immune pathways

- ISR–Induced Systemic Resistance
- SAR–Systemic Acquired Resistance

Activation of these two pathways occurs via two methods. First is the aggregation of strong microbes in the rhizospheric regions that release immunity-triggering metabolites into the plants. The second pathway is the increased concentrations of plant secondary metabolites that act as triggering factors.

How Does This Help the Plants?

Activation of plant immune pathways renders them completely resistant to all kinds of beetles, including Japanese beetles, Colorado potato beetles, squash bugs, corn rootworm beetles, cucumber beetles, etc. Resistance to root rot nematodes and some viruses has also been observed in some cases. Plants require a rich mix of microbes in the plant microbiome to trigger the immune pathways. We can also assist this stage through foliar application of chitinase, chitosan, seaweed, Japanese knotweed extract, and ISR and SAR-triggering rhizobacteria. Only after the completion of this stage, can we claim that the complete potential of a plant is attained.

These stages of plant health help us look at plant–soil interaction from a whole different perspective. All four of these stages reveal the importance of soil health in determining the health status of plants. The first two stages are dependent on the nutrient profile of the soil while the other two are dependent on the richness of the rhizospheric microbiome.

That’s a lot of soil science that we covered so far. It’s always the best idea to learn theory before starting on the practical. Now that you have grasped the main principles that rule soil biology, it’s time that you bring out your inner scientist and start working with your soil.

4

GETTING TO KNOW YOUR SOIL

I always tell people that their success with farming is dependent on how well they interact with the soil and how well they know about the characteristics and deficiencies of their soil. We have seen how soils all over the world vary in their mineral composition, how soil organisms influence their productivity, and how environmental factors transform them over time. But how do you figure out which soil type you are working with? What are its pros? What are its deficiencies? How rich are the microbial communities in your soil? And what is the pH of your soil?

Let's get started with a couple of soil tests that will help you get the answer to all of the above questions. These tests will help kickstart your soil regeneration journey by highlighting the problematic areas of soil.

The Soil Jar Test

The soil jar test is the easiest at-home method to establish the composition of the soil. Recall the different soil types that we discussed in chapter 1 and how each of those soil types varies in their nutrient and water retention capacities. This is what this test will help you determine. Once you have established the composition of the soil, you will be able to determine the type of soil amendments that the soil requires. For instance, if your farm has clay soil, you will want to look for methods to help with water drainage since clay soil does not drain well, resulting in soggy roots.

Starting without knowledge of your soil type creates problems later on during the plant growth stage, which is not the ideal time for soil amendment. Determination of soil composition is not a difficult task, and it doesn't require costly devices either.

Apparatus and Materials

- 1-quart transparent jar with a tight-fitting lid
- a trowel
- soil sample
- clear water
- a teaspoonful of dishwashing liquid

Procedure

1. To collect a soil sample, dig soil down to about 15-20 cm. Don't just scrape the surface; you need to get a good cross-section of soil that includes all of the major layers of soil.
2. Sift the soil using a kitchen strainer. This will break soil lumps into individual particles and separate out unwanted material like dead roots, insects, and rocks.
3. Fill half of the mason jar with your soil sample.
4. Add water to fill the jar three-quarters full.
5. Add a teaspoon of dishwashing liquid to it.
6. Close the lid tightly on the jar.
7. Shake the jar vigorously for about three minutes.
8. Set it aside for about 24 hours for the soil to settle down.
9. You will determine if your results are ready for interpretation by noticing the water turbidity. Water will not clear out completely, but its turbidity will lessen with time. If it's still extremely turbid, leave it for another 48 hours.
10. Notice the different soil layers formed at the bottom of the jar and determine your soil composition based on these layers.

If the area that you want to cultivate is large and contains different soil types (which you'll know simply by looking at it or running it through your fingers), it is suggested to perform a separate test for each cultivable region.

Interpret Your Soil Composition

Mason jar test results are easy to decipher. Due to the presence of water, each kind of soil particle will sediment based on their densities. The dense particles like that of sand and gravel will sediment quickly to the bottom. Silt particles are less dense so they will take some time to sediment and layer on top of the sand. Lastly, clay particles being the lightest will sediment loosely at the top.

Given below are the criteria to help you determine your soil texture:

- Sandy soil—if the last layer in the jar is the thickest layer (i.e., sand), this means your soil is sandy. Water in the jar will be very clear since the number of suspended clay particles will be fairly low.
- Clay soil—a jar having clay soil will have the most turbid water since a huge amount of clay particles will remain suspended in the water. Two to three extremely thin layers of sand, silt, and clay will settle at the bottom. Even the slightest movement will disturb the sediment clay particles back into suspension.
- Peaty soil—if you have a jar that has small sized-debris floating at the top with a thin layer of sediment of soil at the bottom, your soil is peaty. Such soils are composed of large-sized organic particles as well as small-sized clay and sand. Clay and sand do not sediment easily, thus giving a murky look to the water. Such soils are acidic and have a low mineral profile, therefore, needing to be amended. The high water-holding capacity of organic matter makes this soil prone to waterlogging.
- Chalky soil—this clay will give your soil solution a whitish look. Particles of chalk

will be present both in water as well as in a layer at the bottom of the jar. Such soil has poor organic content as well as lower water-holding capacity. Due to the presence of chalk, this soil has alkaline pH.

- Loamy soil—all components of this soil will sediment in neat layers at the bottom of the jar, and water will be the least turbid. This is the soil that all growers and farmers wish to have, so if your jar test shows the presence of this soil, you have great soil composition!

Having loam soil is a rare occurrence especially since anthropogenic activities have damaged most of the soils, but if you are lucky enough to have it, you won't have to invest in soil amendments. However, if you have any other soil type, you will have to do some work before you can start cultivation.

- Clay soil will require the addition of OM to increase pore size between soil particles and to improve water drainage.
- The addition of compost may help improve the water retention of sandy soil.
- Green manure and compost will improve the condition of chalky soil.

Getting the Soil pH Right

Do you remember the chemistry lessons about pH that you took in high school?

pH is a measure of hydrogen ion concentration in any material. This relative concentration of hydrogen ions determines how the material behaves in its chemical reactions. A scale from zero to fourteen is used to depict the pH values of different solutions. Values from zero to six show acidic pH, seven is considered neutral while eight to fourteen is the pH that shows basicity or alkalinity.

How Does pH Affect Soil Chemistry?

pH is involved in everything present on this earth whether it's the food we eat, the water we drink, the air we breathe in, and the soil we grow our food in. For soils, even the smallest pH fluctuations could mean drastic changes in soil biochemistry. This could affect the bioavailability of minerals and the activity of soil organisms, especially bacteria and fungi.

Most minerals and nutrients are available to plants at a neutral pH but there are a few nutrients that are specifically associated with acidic or basic pH ranges. Deficiency or excess of certain plant nutrients can drastically damage plant health. This means that pH is very crucial in determining the success of stage 1 of plant health (i.e, complete photosynthesis). Soils with acidic pH often have toxic levels of magnesium, manganese, calcium, aluminum, and phosphorus. On the other hand, extremely alkaline soils may have toxic levels of sodium and deficiency of copper, zinc, manganese, and boron. Such soils are suitable for plants with special nutrient requirements but normally, neutral soils with a balanced concentration of nutrients are suitable for most plant species.

Bacteria and fungi are sensitive to pH fluctuations as each species show optimum growth only at a narrow range of pH. Acidophile bacteria grow in extremely acidic soils while alkaliphiles thrive in alkaline environments. However, most bacterial species are able to survive at a pH range of five to seven; we call them neutrophils (Jin & Kirk, 2018).

Additionally, plants are also choosy when it comes to soil pH. While most plants grow at a wide range of pH, their optimum growth is observed only at specific pH values. For example, blueberries are acid-preferring (with optimum pH of 4.5–5.5). If you plant them in neutral soil, they may grow ,but the plants will be weak and have yellow-colored leaves (Longstroth, 2012).

Naturally, a soil's pH is a function of its parent material. But once it is formed, geological and environmental factors change this pH over time. These factors include climate, rainfall, topography, flora, and fauna. In the last few decades, anthropogenic activity has deeply affected the pH of soils around the world.

How To Measure Soil's pH?

You can use several options to measure the pH of your soil. There are commercially available kits that come in a variety of price ranges. These pH kits are easy to use and give an approximate value of pH. Then there are agricultural labs that have advanced equipment for measuring pH down to the decimal value. However, I recommend the DIY strategy. There are a few inexpensive methods that you can use to determine the pH of your farm soil. These DIY methods

- are inexpensive.
- require no special equipment.
- can be done often to keep a track of pH fluctuations throughout a growing season.

pH Test With Baking Soda and Vinegar

Materials

To perform this test you'll require

- a soil sample (from the area that you want to cultivate)
- a pair of non-reactive containers (made of plastic, ceramic, stainless steel, glass, or enamel-coated metal)
- a non-reactive utensil (for handling soil)
- half cup vinegar
- half a cup of baking soda
- mineral water

Procedure

1. Dig a 15 cm hole in four to five different spots in the yard.
2. Collect one scoopful of loose dirt from each of these holes and put all of it in a container.
3. Mix this soil thoroughly.
4. Divide your soil sample into equal parts, putting each part separately into its own non-reactive containers. Each container should have at least half a cup of soil in it. The utensil used for transferring the soil samples should be sterile and made of a non-reactive material.
5. Add half a cup of vinegar to the first container. You can use any form of vinegar so long as it has a concentration of five percent.

6. Note what happens to the soil sample. If it starts to fizz, it means that the soil has an alkaline nature. The intensity of the fizzing will show how alkaline the soil is. If there is a light bubbling in the soil mixture that subsides quickly, your soil is slightly alkaline with a pH between 7.5–9. However, if there is a lot of fizzing upon the addition of vinegar, your soil is highly alkaline, and you will have to use soil amendments to bring this pH down.
7. If your soil has shown a reaction with vinegar, your soil's pH is established (it's alkaline!), and you don't need to proceed with the second part of this test. Start thinking of which soil amendment you will be adding to deal with alkalinity.
8. However, if the soil has not reacted with vinegar at all, proceed with the second part of this test which requires testing your soil for acidity.
9. To do this, add a little water to your second soil container to make a thick paste.
10. Now, add half a cup of baking soda to it.
11. Most likely, your soil sample will start reacting with baking soda which will be visible to you in the form of bubbling of the mixture. Bubbling of soil slurry will indicate an acidic pH of 4–5.
12. If your soil is acidic, you will have to lower this acidity before planting anything in it.
13. However, if your soil still doesn't react, that's a good sign; your soil is neither acidic nor alkaline. That means it has a neutral pH and is perfect for growing almost everything.

pH Test With Red Cabbage

Materials

- soil sample
- 1 medium-sized red cabbage
- 2 cups distilled water
- saucepan
- non-reactive spatula
- knife
- 2 non-reactive containers
- strainer
- teaspoon

Procedure

1. Take two cups of distilled water or mineral water in a saucepan. You can use home-purified water as well, but I recommend using distilled water as it is totally free of minerals and other impurities (which can offset your test results). Distilled water is commercially available at pharmacies and supermarkets.
2. Add one cup of finely chopped red cabbage to the saucepan.
3. Let it boil for ten minutes. The color of the cabbage will slowly start mixing with water. This red color of cabbage is due to the chemical anthocyanin, which will serve as an indicator for your pH test.
4. After ten minutes, turn down the stove to medium-high heat. The water will gradually

turn to a deep violet color. Don’t boil the cabbage too long or it will give a blackish color to the water and get hard for you to distinguish color during the pH test.
5. Once a deep violet color is obtained, turn off the stove and strain the solution to collect water in a separate container.
6. Set the container aside for ten minutes to allow the water to cool down.
7. Transfer the water into a non-reactive container.
8. Collect the soil sample from four to five different locations in your growing area. Remember to dig at least 15 cm deep to obtain a good soil sample. Don’t just scrape the surface.
9. Mix the soil using a non-reactive spatula.
10. Sprinkle two to three teaspoons of soil into your violet-colored test solution and wait for it to change color. Color change of your test solution will indicate the pH of your soil.
11. If the solution turns green or turquoise, your soil is alkaline having a pH between 7.5–8. If the color lightens to a deep shade of pink, then your soil is acidic (somewhere in the range of 5–6). However, if the color does not change upon adding soil, your soil is at a neutral pH.
12. Once you have determined the approximate pH of your soil, you can take the necessary actions to fine-tune your soil’s pH within a suitable range.

You might need to repeat these tests often to keep a record of your soil pH. These pH tests are a fun activity where you can involve kids too. Activities like these will help build their interest in the soil and allow them to see soil as a living entity, one that needs their attention and care.

Soil Mineral Testing

Soil mineral testing is one of the most frequently done tests that farmers and agriculturists perform on their land. This test determines the minerals that are readily available (or will be available in a few years' time) to the soil and plants. It basically measures the soluble mineral content of the soil while highlighting the mineral deficiencies and toxicities. Additionally, it also shows the overall makeup of the soil. This information helps the farmers and gardeners to make informed decisions about their soil.

For this purpose, easy-to-use kits are available commercially that can provide you some insight into the soluble macronutrients and micronutrients of your soil. Some people also like to consult the bioregional records of their area to gather knowledge about the parent material and common nutrient imbalances in their area.

Does this test reflect the exact quantity of minerals in your soil? No, it doesn’t. Because even when you test a number of sites, you can’t possibly scan the entirety of your land, and so, the data you receive will give you a rough estimate of what is abundantly present in your soil, what is severely lacking, and what should you expect in the years to come.

However, one thing that this test will not tell you is the insoluble mineral content of your soil. This includes the mineral content that is present in the bound insoluble form that needs biological and chemical transformation to become soluble. Such content requires several years of biological and weathering changes to become available to the soil. For instance, if your soil has feldspar, the aluminum and sodium metal in it may not dissolve rapidly, however, rock weathering may release these metals in a decade or so, leaching metal toxicity in your soil. Such minerals will become detectable when they are in their soluble forms.

Plant Sap Analysis

Unlike a soil mineral test, sap analysis provides a clearer picture. In fact, this test is even better than most of the other mineral tests. It measures the actual amount of nutrients that are moving around in the circulatory system of a plant.

As the name suggests, this analysis is based on plant sap which is collected and used to quantify each kind of sugar, macronutrient, and micronutrient that is present in the plant. It also gives the quantities of different forms of carbohydrates and nitrogenous compounds present in the sap. The efficiency and accuracy of this method have made it extremely popular compared to its competitors like the BRIX meter and CARDY ion meter. It doesn’t simply relate what might be happening or could happen to your soil within a few years' time, it communicates exactly what is currently happening in the soil, what the soil is lacking, and what it needs.

How Can Sap Analysis Help Farmers?

When done periodically, sap analysis can serve as a meter to gauge the fluctuation in the soil’s nutrient profile and its effects on nutrient availability and plants’ sap composition. This periodic analysis can be done by comparing the sap of old leaves with the newest leaves of a plant.

This test can answer a number of queries for farmers. For one, this test can serve as a determinant of plant health (remember the four stages of plant health). The presence of macro and micronutrients required for photosynthesis can confirm stage 1 of plant health. The absence of active nitrogen compounds will indicate that all of the nitrogen is converting into amino acids and there is no circulating nitrogen in the system (stage 2). In case a previous sap analysis has revealed the scarcity of certain nutrients and you are applying fertilizer to overcome that deficiency, sap analysis can help you confirm whether the nutrient is reaching your plants or not. It’s not wise to continue investing in fertilizers when they are leaching out or unable to get into the plant. Periodic sap analysis can help farmers know about the changing soil conditions over a season and make informed decisions about the use of mineral amendments, biofertilizers, and cover crops.

John Kempf’s website, Advancing Eco-Agriculture, offers sap analysis services. Anyone can visit their website to place an order for a sap analysis kit. On receiving your kit, you have to collect two separate samples consisting of old and new leaves and ship them to the testing lab. After the analysis is complete, the results are sent to you. These results consist of 23 data points which represent macronutrients, micronutrients, sugars, pH, multiple forms of nitrogen, and trace minerals. You can then analyze the results with a consultant and devise a plan to amend the problems highlighted in the report.

What Is Living in Your Soil?

The importance of soil organisms can never be overstated. By now you should have a very clear idea of how important soil organisms are for plant health. It is these living organisms that render “liveliness” to the soil. So now that we understand the ways to measure components of soil, let’s uncover some ways to determine soil organisms.

Microorganisms

You can easily visualize the microorganisms present in your soil with a simple microscope. This will help you get a rough idea about the number of bacteria, fungi, protozoa, and other microorganisms present in your soil.

Apparatus and Materials

- soil sample
- microscope (with 400X magnification at least)
- trowel or apple corer
- 1 container
- 1 container with a tight-fitting lid
- ¼ cup water
- pipette and pipette tips
- glass slide
- cover glass

Procedure

1. Select 5–6 different spots in your garden/yard that you want to check for microorganisms.
2. Clear the areas of vegetation and other debris.
3. Using a trowel, dig a 5–6 cm deep hole in each of these spots. Alternatively, you can use an apple corer to collect your soil sample.
4. Collect a small amount of soil from each hole and put all of it in a single container. Mix thoroughly to create a single sample that represents the whole area under study.
5. Add 5 g (about 1.5 teaspoons) of soil to a container.
6. Now add 145 g (1/4 cup) of water.
7. Close the container tightly with a lid and shake for about five minutes.
8. To observe your soil sample under a microscope, you will need to set a microscope. Prior knowledge of microscopy will help you at this point. However, if it is your first time using a microscope, you can ask a lab technician to assist you.
9. Open the lid and using a pipette, draw up one to two microliters of your soil suspension. It's best to not draw up large soil particles as they will disturb your cover slip.
10. Eject the sample on the glass slide.
11. Hold a cover glass by the edges, and place one of its edges close to the sample drop such that it is making a forty-five-degree angle with the glass slide.
12. Slide the cover glass gently over the sample drop to spread it.
13. Slowly place the same cover glass onto the evenly-spread sample smear. Try not to trap any air bubbles while doing so.
14. Place your prepared slide on the microscope stage and place the clip on the side of the slide to hold it firmly in place.
15. Start examining your slide using the lowest magnification, and use different focuses to improve the image.
16. If the image is not improving switch to a higher magnification, and repeat this until a

clear visual is obtained.

17. Then, focus on each section of your smear and take notes of your observations. The instructions given below will help you identify different microorganisms.

Microorganism Identification Guide

There are four broad categories in which we divide soil microorganisms, namely bacteria, fungi, protozoa, and microscopic animals.

Bacteria Identification

Bacteria will be present in three basic forms each of which exhibits a specific motion:

- Round—these are called cocci, and you may find them vibrating or moving in a straight line.
- Rod-shaped—these are called bacilli, and you may find them in a straight or zigzag motion.
- Spiral-shaped—these are called spirilla, and you may find them rotating like a corkscrew.

Fungal Identification

Fungal bodies exist in the form of long threads called hyphae. These fungal hyphae are two to six times larger than bacterial cells. Under a microscope, hyphae are visible as long brown threads either dispersed throughout the slide or joined end-to-end to form a single long strand.

Protozoa Identification

Protozoa are incredibly diverse single-celled organisms. They are a lot larger and more active than the bacterial cell, which makes them easy to identify. Since protozoa feed on various bacteria, their active presence in a soil sample indicates bacterial diversity. In terms of shape, size, and cellular motion, protozoa are divided into three main types:

- Amoeba—the largest protozoan type with a size ranging between 10-50 micrometers. They don’t have a fixed shape and move around by dragging themselves using their false feet. I like to think of an amoeba as a small splotch or a blob moving slowly in a fluid-like motion. The actual term used for splotch-like amoeba is “naked amoeba,” while blob-like amoeba is known as “testate amoeba.” They are abundantly present in all kinds of soil due to their flexibility, which allows them to penetrate even the smallest soil pores.
- Flagellates—the smallest form of protozoa that ranges in size between 3–10 micrometers. They usually have a “limb” attached to their body that they use to move around. They usually move in a rocking or twitching motion.
- Ciliates—the most diverse form of protozoa in terms of shape and size. As their name suggests, they have tiny hair and cilia on their entire body which help them move around at much faster speeds than other protozoa. Remember, most of the ciliates are anaerobic and can be a sign of compacted or waterlogged soil conditions.

Identification of Microscopic Animals

These are multicellular organisms that have a variety of shapes and sizes. Compared to other soil, microorganisms are quite large, which makes them easy to identify. These animals have a simple digestive system that allows them to consume a variety of soil bacteria and fungi. Microscopic animals are abundant in soils that are rich in OM. The three common types of microscopic animals include:

- Nematodes—have long cylindrical bodies.
- Rotifers—look like beetles with several distinct body segments.
- Tardigrades—often called moss piglets and water bears due to their appearance.

Dr. Elaine Ingham has established a checklist for what an ideal soil sample should look like. According to this list, a particular area of the microscopic slide should have

- hundreds to thousands of bacteria per field of view (the maximum area visible when viewing a slide under a microscope).
- one or more strands of mycorrhizal fungi every five fields.
- one or more amoeba or flagellates every five to ten fields.
- at least one nematode on a microscopic slide.

Establish Your Soil's Succession Level

Once you have determined the diversity of microorganisms residing in your soil, you can use this to establish the succession level of your soil. Succession level refers to the complexity of an ecosystem which directly depends on the age of that ecosystem. Let us take a look at major soil succession levels.

Pioneer Level

As the name suggests, this level consists of pioneer organisms that inhabit a particular area and set up an ecosystem. In soils, this succession level comprises mainly of bacteria, a few protozoa, and some thin fungal hyphae. Such soils have higher mineral content but are deficient in OM, which leads to poor soil aggregation.

Middle Succession Level

As the pioneer organisms populate the ecosystem and more complex organisms start to live in an ecosystem, its succession level progresses to the middle tier. These organisms are more sophisticated in their structure and rather choosy in their diet. The most common soil organisms at this stage are bacteria and fungi. An almost equal number of these two organisms provides soil with better organic matter and soil aggregates. Protozoa are abundant at this level and easy to observe under a microscope.

Climax Level

Soil with this succession level looks very organized and clean under a microscope. This level has the highest biodiversity. The number of free-living bacteria is low and the number of fungal hyphae is extremely high. The number of microscopic animals is abundant, and soil aggregates are held strongly together with OM.

After you have determined the succession level of your soil, you can devise a plan to improve or sustain that level. Factors that can help improve the succession level of soil are

- aeration
- moisture retention
- nutrient supply
- shelter and reduced disturbance
- increased macroorganism activity

We will discuss all of these factors in part II of the book.

Macroorganisms

To get a rough estimate of macroorganisms present in your soil, you can perform some simple observation-based tests. Since these organisms are “macro,” you can easily see them with the naked eye.

General Test for Macroorganisms

You already know how important the role of soil’s macroorganisms play in determining its fertility. Well, a complex web of earthworms, beetles, millipedes, and other invertebrates plays a crucial role in improving soil structure and nutrient profile.

To measure these organisms you can perform a simple test. All you need to do is dig a six inch-deep hole anywhere on your land and look into it for four minutes. Keep a notepad and a pen with you to note the number and type of every macroorganism you find. You can gently mix the soil to stir the bugs that may be inactive at that time.

You should be able to find at least ten bugs in that hole to declare your soil rich in microorganisms.

Test for Earthworms

To estimate the number of earthworms in your soil, you first have to select a perfect location that shows evidence of earthworm activity. Scan your soil for signs of “worm poop,” which will exist as small piles of turned-up soil or as tiny pellets of soil. After you have located such a spot, dig a spadeful or two of soil from that area and spread it on an old newspaper.

Take a chopstick or any similar object and start dissecting this soil for earthworms and cocoons. Note the number and type of earthworms that you have unearthed.

For soils where you don’t find clear evidence of earthworm activity, you may have larger, deep-burrowing earthworms that reside deeper in the soil layers. To expose and identify such organisms, there is another fun activity that you can try. However, keep in mind that it will not work in hot climates where earthworms rarely exist (since they hate hot environments).

1. Start off by marking your “area under study” with a string and four cardboard pieces.
2. Thoroughly mix ¼ cup of mustard powder in a gallon of water.
3. Slowly pour this mustard water inside your marked area.
4. Allow a few minutes for the water to penetrate into the ground.

5. As soon as the mustard solution soaks into the ground, earthworms will start appearing on the top. Mustard will irritate their skin and make them move swiftly toward the soil surface.
6. Pick them up one by one using forceps and put them in a water-filled container to rinse off mustard residues.
7. Note their number and whether they are all the same or not.
8. Once you have done so, release them safely back into the soil.

How to Determine Your Water Needs

There are a lot of technical concepts involved when it comes to measuring soil's water requirements (in relation to plant growth). However, we will use a simple test that will help you determine whether the amount of water you are adding to the soil is seeping well into the ground or is being lost as runoff.

To do that, you need to perform a water infiltration test.

Water Infiltration Test

For this test, all you need is an empty plastic bottle (with its bottom removed), a permanent ink marker, a ruler, and a timer.

Procedure

1. Take the plastic bottle and push it completely into the soil leaving only three inches above the surface.
2. Mark these three inches with a permanent marker to track the rate of infiltration.
3. Now pour water into the top of the bottle and start the timer.
4. Note how much time it takes for all three inches of water to infiltrate the soil. Repeat this process two to three times and then calculate a mean.

Consider the following example:

Water Infiltrated (in inches)	Time Taken (in hours)	Infiltration Rate (inches/ hour)	Mean Infiltration Rate (Sum of infiltration rates / total readings)
3	4.2 hrs	0.71	(0.71+0.66+0.65)/ 3=0.67
3	4.5 hrs	0.66	
3	4.6 hrs	0.65	

Soil with an infiltration rate of a half to one inch per hour is considered good. This means that the infiltration rate in the example above indicates normal soil with a good infiltration rate of 0.67 inches/hour. An infiltration rate lower than a half inch per hour indicates problematic soil with small pore size and high compaction. Such soils lose water through runoff and are prone to erosion. If your soil has this issue, you'll have to look for ways to amend it or work with it.

Water Availability Test

This test will determine how long water stays in your soil before being lost to evaporation. This is the easiest test and you won't need anything special to carry it out.

Procedure

Just wait for heavy rain. After the rain, you will not need to water your plants for a few days. Your task is to notice exactly how many days before your plants start to show signs of thirst. This will reveal how frequently your plants need watering. If you notice that they need water more frequently than typical for your regional vegetation, there might be a problem with your soil.

An ideal soil will have sufficiently large pores that hold water and resist evaporation while also allowing plant roots to receive as much water as required.

Performing all of these tests on your soil will give you a better understanding of the type of soil that you are workingwith. Depending on the area of your land, you may need to perform these tests at multiple spots. This is especially important for large farms that may have different soil characteristics in different parts.

So, What Did You Learn So Far…

- Anthropogenic activities are throwing off the balance of ecosystems including the soil ecosystems.
- Humans are continuing to neglect the climate emergency and failing to adopt a sustainable lifestyle.
- "Living soils" that have taken billions of years to form are being destroyed due to a lack of regenerative agricultural practices.
- Biogeochemical cycles have been thrown out of balance in several areas of the world which is threatening the integrity of terrestrial and soil food webs.
- Successful attainment of plant health stages can render plants resistant to several diseases and pests.
- Organic matter and soil organisms are two important determinants of soil fertility.
- Performing a few DIY soil tests can help you better understand your soil and decide on any soil amendments or remedial actions that it may require to ensure the health and sustainability of your soil.

PART II

5

WHY NO-TILL IS THE WAY TO GO

In part I, we have discussed factors that define and maintain the structural and functional integrity of the soil. Soil is a resilient entity, but lack of proper care and intense agricultural practices can destroy its vitality.

In this section, we will be focusing on soil remediation and regeneration which is rooted in nature. We can facilitate soil health by following some easy soil regenerative strategies and allowing nature to do the rest of the job.

What Is Tilling and Why Was It So Popular?

If you are a farmer or learning to be one, you will be aware of tilling. It is, after all, the most-popular soil preparation method, and people have been using it for centuries. Historical records suggest that tilling (also called plowing) has been an integral part of soil preparation practices since the 1700s (*Jethro Tull (Agriculturist)*, 2019).

Tilling is the practice that involves turning and loosening soil before cultivation. It is done to facilitate soil's nutrient uptake and gaseous exchange. A variety of automatic rototillers and cultivators are available for tilling although some people prefer hand-held tillers to till their yards and gardens.

Development of Tilling Through the Ages

The concept of tilling is backed by several years of scientific research, and although most of it has been discredited now, tilling still remains to be the most practiced soil preparation technique.

It all started in the 1500s when Bernard Palissy proposed the idea that plants take up "salts" from the soil which are then returned when plants and animals decompose. His ideas were similar to the concept of nutrient cycling. This work was followed by similar works by other researchers. In the 1600s, water and air were proposed to be important soil components that plants need to flourish. Later on, it was proposed that plants actually obtain pulverized soil particles to draw essential nutrients and moisture from them. This concept highlighted the importance of soil tilling (pulverization).

So, when Jethro Tull of England invented the first soil cultivator in the 1700s, people were very receptive to his ideas and quick to adopt his soil cultivation practices (Daigh & Hughes, 2018). The studies that followed strengthened the idea that nutrients, water, and air collectively maintain plant health; however, they still didn't recognize that nature has its own mechanism for providing these components and that no external assistance is required. Meanwhile, the "tull cultivator" continued to gain popularity among farmers and growers. The three factors that follow made tilling an essential part of agriculture and farming:

1. Reduced Soil Compaction

We have seen how important it is for soil to have a sufficient number of pores to:

- hold nutrients.
- allow gaseous exchange.
- retain water for plants.

Compacted soils are not very good for the plants because such soils don't offer sufficient aeration, leaving plants looking dull and dry. Tilling is a quick way to provide aeration to such soils that have been compacted due to excessive foot traffic or heavy machinery. Well-aerated soils allow plant roots to exchange water and gasses with soil solution. These soils have efficient nutrient cycling systems.

2. Mixing of OM

Have you ever thought that your soil was becoming less fertile because of continuous cultivation so you added a layer of manure or green fertilizer on top of it, but that still didn't change anything? That can happen for a number of reasons including soil compaction and lack of soil organisms. Tilling can provide a quick fix to this problem by mixing the OM/fertilizer well with the soil.

3. Elimination of Pests and Weeds

Tilling gained popularity among farmers partially because it offered a cheap fix to their weed and pest problems. Weeds and insects are big issues for farmers as they can limit the final yield of a crop by destroying fruiting parts of plants or hindering their growth. Tilling soil can effectively deal with weeds by destroying their seeds and roots. This can also lower the occurrence of pests, especially the ones that burrow in the soil.

The Downside of Tilling

It was in the 1850s when researchers finally started to notice the undesirable effects of tillage and after researching soil organisms and their role in nutrient mixing, they finally started to question the vitality and safety of tilling practices. There were mixed reviews on whether tilling did or didn't improve crop yields. In the 1900s, clear evidence of soil washing (the old term for soil erosion) and an accompanying decline in yield were reported (Daigh & Hughes, 2018).

To investigate the cause of declining yields of tilled soils, several studies and research were conducted, and the following drawbacks of tilling were brought to light:

Soil Erosion

Tilling disturbs the top layer of soil (topsoil), making it more susceptible to soil erosion. Such loosened soil is easily eroded away by high winds or lost to runoff.

Water Pollution

Topsoil lost to runoff often carries fertilizers and chemical additives that are applied to the soil. These fertilizers and chemicals enter the water bodies where they contribute to water pollution. The quality of drinking water is also compromised.

Eutrophication

Components of phosphorus and nitrogen fertilizers contribute to eutrophication upon entering lakes and streams.

Loss of Organic Matter

Even though tilling mixes the organic matter well with the soil, it can also cause a loss of OM over time. Loss of organic matter is the leading cause of decreasing productivity of tilled soils. The water retention capacity of soil is also lowered.

Disruption of Soil Structure

Loss of topsoil along with OM puts the lower soil layers at a high risk of damage. Remember that soil particles are held together as larger soil aggregates, which creates pores between them for gaseous exchange and water infiltration. Crumbling of these soil aggregates removes these pores and puts soil at a greater risk of compaction. Other functions of soil like a gaseous exchange and water infiltration are also disrupted.

Reduction in Carbon Sinking Capacity

Tilling is also known to release a lot of stored carbon into the atmosphere (as carbon dioxide) by increasing its mineralization rate. Silva-Olaya et al. (2013) have reported that the amount of carbon emission (measured during the renovation of sugarcane fields) is a lot higher in conventional tilling systems than in minimum tilling or reduced tilling systems.

Increased Weed Production

As mentioned earlier, weed control was a major factor that compelled masses to adopt tilling practices, but it was later found that even though tilling may hinder weed growth for a limited period, it cannot eliminate them completely. In fact, it may bring dormant weed seeds to the top and spur their growth. In short, tilling your soil for weed control is like trading one weed for another.

Disruption of Soil Food Web

Do you think that you can till your soil without actually disturbing and, in some cases, completely destroying the soil food web? No, that’s not possible. Organisms residing deeper in the soil may not be affected directly, but the organisms that live near the topsoil will be disturbed. This will offset the balance between different trophic levels and soil structure, and plant health will suffer.

In the long run, tilling can completely destroy soil by damaging its mineral content and halting microorganism activity. This can ultimately lower plant yields by limiting root elongation and meristematic growth of other plant parts.

The revival of soil after being damaged by continuous tilling takes a long time. You can imagine how much additional expense this kind of soil will incur for rehabilitation and regeneration. Farmers will need to spend more on soil amendments and fertilizers to rebuild soil structure and improve its organic content. And while most of the soil characteristics can be restored through soil additions, the presence of a favorable subsoil layer is essential to support this process. In the presence of unfavorable subsoil conditions like a limited root system and deficiency of sand and gravel, the recovery process has limited chances to succeed. In such a case, there is a permanent loss of productivity.

What Is No-Till Method and What Makes It Better Than Tilling?

The period of the “dust bowl” that eroded away most of the agricultural topsoils in America and Canada made people think of soil conservation practices. Research on the disadvantages of tilling was also an eye-opener, but the final blow for tilling strategies came when environmental activists and biologists started advocating for ecosystem conservation. This shifted the focus from moldboard plow to chisel blow. A moldboard plow cuts the soil and turns it over (imagine how damaging that can be!), while a chisel plow only combs through the soil while keeping most of the material undisturbed.

The discovery of commercial pesticides and herbicides made people abandon tilling as a means of controlling weeds and pests. Finally, by 1970, the no-till strategy started to gain popularity.

As the name suggests, the no-till method excludes all forms of tillage practices from soil cultivation. The soil is left completely undisturbed except for the one time when seeds are sown. No-till farming/gardening means growing plants continuously for several seasons without disturbing the soil and letting nature do its job.

Both soil and plants can benefit from the no-till method in several ways:

Reduced Soil Erosion

This is the biggest benefit of no-till farming. We are already seeing so much soil erosion due to urbanization, deforestation, and industrial activity. Therefore, a little reduction in tilling will hugely benefit agricultural lands all over the world. In fact, it has been estimated that a complete shift to no-till agriculture will lower soil erosion and sedimentation by more than 70% (Stein, 2021).

Reduced Water loss

In agricultural lands, water loss occurs through runoff and evaporation. No-till farming is known to lower the rate of both of these processes, thus retaining water in the soil. No-till soils have a high ratio of organic matter, meaning they have a high water retention capacity and therefore reduce water loss from runoff.

Excessive water loss through evaporation is also a serious concern, especially in arid and semi-arid regions. Tilling breaks the soil structure and exposes the stored moisture to evaporation and this causes rapid drying of topsoil. No-till strategies steer clear of this problem by keeping the moisture locked up in the soil.

Preservation of Soil Organisms

The no-till strategy helps soil organisms in a number of ways. First, it reduces soil disturbance which is the topmost requirement for soil organisms to thrive. Second, the reduction of chemical fertilizers help them to grow in a chemical-free environment.

Preservation of Soil Structure

No-till method ensures that the inherent soil structure remains intact. Soil structure is crucial for the health of the plants and animals that are associated with the soil. The preservation of soil structure is the key to sustainable agriculture. This means that even when we are using soil for plant growth, we are ensuring that soil maintains its inherent characteristics. Soil formation is a long process, and we don't want to destroy something that requires so much time to create in the first place.

Nutrient Replenishment

No-till soil is self-replenishing. While we can increase the organic content of these soils by adding mulch and other soil additives, plant roots that are left in the soil can act as a rich source of organic matter. The decomposition of these dead roots adds nutrients to the soil.

Quick Transition to Higher Succession Levels

It takes a long time for soils to reach higher successions levels, and excessive tilling can degrade them back to lower levels. Tilling can destroy fungal hyphae and upset the ratio of bacteria and fungi. The no-till method can effectively deal with this problem by boosting the growth of both bacteria and fungi, thus helping the soil organisms facilitate higher succession levels.

Limited Use of Heavy Machinery

Limited use of heavy machinery on no-till farms lowers the chances of soil compaction. This ensures that soil organisms residing in the topsoil are not harmed. Another benefit of limiting heavy machinery use is that farmers don't have to spend much on maintenance or fuel. In short, everyone wins!

Environmental Benefits

The addition of mulch and other amendments over the topsoil not only provides nutrients to the subsoil, but provides a few other notable benefits. First, it provides a cover to the fauna residing under the soil. Second, it protects the topsoil from the effects of rainfall and winds, thus preventing soil erosion. This thereby maintains the carbon holding capacity of the soil, and water retention capacity increases.

Since the no-till method ensures nutrient replenishment, a final and crucial benefit is the decreased need for artificial fertilizers, which, in turn, decreases the risk for environmental and water pollution.

Getting Started With No-Till Farming

A complete transition from till to no-till farming requires a 180-degree shift to your land management practices as well as your mindset. I know many farmers who struggled a lot while making this transition. In my view, that's because we have always seen tilling to be an essential part of soil cultivation, and it's difficult to abandon it completely.

I remember when I first started gardening, I loved tilling my soil. This was still the time when tilling was considered an efficient way of aerating the soil and mixing organic content with it. When I learned about the no-till method and tried to implement it in my garden, I was frustrated at first. Because, let's face it, no-till farming is not an instant formula, and it needs time to take effect. I often thought of switching back to tilling. I now feel guilty about the damage I inflicted on my soil in my initial days and absolutely love the effects that my no-till strategy is producing.

No-till farming is an easy method that entails a number of techniques to help plants achieve the same benefits that tilling would offer, in addition, of course, to the valuable benefits the no-till method has to offer. And since it is a method that mimics nature, there are hardly any drawbacks from it. Take a look at some of the basic no-till strategies and the benefits that they offer.

These strategies include:

- using cover crops
- choosing plants that aerate the soil
- mulching

The Benefits of Cover Crops

Cover crops are the crops that are planted to enrich the soil with organic content while also helping the diversity of soil organisms. I like to call them "recover crops" because they really help the soil regain its fertility after the cropping season is over. They also protect soil from erosion, runoff, and weeds.

Let's take a look at the benefits that cover crops offer.

Nutrient Addition

Carbon and nitrogen are the two most important plant nutrients which are cycled rapidly between soil, living organisms, and the atmosphere. After a cropping season is over, carbon, nitrogen, and other nutrients need to be replaced back to the soil so that they can support plants in the next season. Planting cover crops is an excellent method to do that. The biomass of these crops decomposes to add carbon and nitrogen back to the soil.

Grasses have a high carbon-to-nitrogen ratio (C:N), which means they add more carbon to the soil than other cover crops. A higher carbon ratio means that they decompose slowly in the soil. Leguminous plants like peas, lentils, soybean, and clover have a low C:N, meaning that they provide a richer source of nitrogen which is released rapidly into the soil upon decomposition.

The age of the cover crop also plays a crucial role in determining the speed at which it releases nutrients to the soil. Young crop residues decompose a lot faster than old, mature crops containing complex carbohydrates which decompose slowly over time.

In addition to adding carbon and nitrogen to the soil, leguminous plants have other mechanisms by which they aid in atmospheric nitrogen fixation. These crops have rhizobacteria living in their root nodules. Rhizobacteria have a symbiotic association with plants where both parties benefit mutually: Plant roots provide food and shelter to the bacteria and bacteria fix nitrogen (as nitrates) for the plants. These plants release nitrates into the soil upon decomposition ready to be utilized by the next crop. Leguminous crops have the potential of adding 50–200 lbs of nitrogen per acre of land. Imagine how much you save that you'd otherwise spend on purchase, transport, and application of nitrogen fertilizers.

OM Enrichment

Most of the cover crops are broken down within 10–15 days, and their conversion to organic matter begins soon after that. Decaying of cover crops adds OM to the soil, improving its nutrient-holding capacity as well as water retention limit. Cover crops are often referred to as “green manure” because they have the ability to increase the organic content of soil by producing high-quality humus.

Soil Protection

Cover crops provide a protective cover to the soil without the growth of a main crop. This prevents the loss of soil from erosion and runoff which is extremely important for areas that are prone to soil loss due to their topology and weather conditions. Cover crops preserve the soil until the main crop is planted. Dense cover crops like buckwheat are known especially for their soil protective features. This dense cover serves a dual purpose: First, it prevents soil from leaving the garden beds, and second, it eliminates the weeds by blocking their access to nutrients and sunlight.

Improvement of Soil Structure

The addition of organic matter through cover crops serves several purposes. Besides improving the fertility of the soil, it also improves its water-retaining capacity. Organic residues reduce surface crusting and lower the risk of soil compaction by creating pores between soil particles. The structure of soil aggregates is improved and the activity of microbes is improved.

Protection From Pests

Once you vow to stop tilling, controlling pests becomes quite a task. However, a number of cover crops are known to have significant pest-controlling properties. For example, Brassica crops (like mustard) are known to deal with harmful nematodes through a process called soil fumigation. Soil fumigation is a process in which chemicals are released into the soil and then turn into a gas that is toxic to soil-borne pests (Cornell University, 2022). Similarly, cereal rye crops are known to reduce the number of soybean cyst nematodes.

Livestock Feed

The usual fate of cover crops is decomposition and decay on the exact spot that they are planted so that they can increase the organic content of the soil, but they can also be grazed or harvested. Crops like wheat, rye, and barley are excellent cover crops for grazing animals.

The selection of cover crops should be based on your soil’s requirements. One way to do that is to divide crops into carbon generators and nitrogen fixers (non-legumes vs. legumes). However, I recommend planting a combination of these two types to replenish both carbon and nitrogen in your soil.

What Is the Best Time to Plant Cover Crops?

There are several things that you should keep in mind while deciding the time to sow a cover crop. A cover crop should be sown at a time that is favorable for it to germinate and establish. Most no-till farmers like to sow a cover crop in the early fall, right after they have harvested their summer crop. However, those who want to grow a winter crop, plant their cover crops earlier by the end of spring. If you want an uninterrupted cropping year, you can plan the timing of your cover crops between your summer and winter crops so that you can revitalize your soil just before the main crop is planted. Some people sow the cover crop just before they start harvesting their main crop so that by the time the harvesting is complete, the cover crop is well established in the soil. But of course, care is required so that the growth of cover crops remains unaffected during the harvest.

The Benefits of Crop Rotation

Even when a thriving soil ecology is sufficient toward removing soil pests and weeds (thanks to cover crops), there is still a chance that soil diseases and pests might attack an area that has not been disturbed for a long time. This problem is effectively dealt with by a technique called crop rotation.

Just like tilling, crop rotation aerates the soil in a way that eliminates soil diseases and pests. Crop rotation promotes soil health by improving its nutrient content and the diversity of soil organisms. This is because each crop has different biochemical characteristics and the introduction of each of these crops promotes a healthy mix of nutrients and soil organisms in the soil.

The idea behind crop rotation is changing the type of plants that grow because you cannot disturb the soil. Each type of plant usually attracts particular kinds of pests and diseases, and continuous cultivation of these plants can place those pests and diseases permanently in the soil. Crop rotation makes sure that this doesn’t happen.

Crop rotation can work in a number of ways. If you are planting a number of plants at a time, you can incorporate crop rotation by switching their locations. Another way to create crop rotation is by completely changing the plant families that you plant in two successive cropping seasons. Let’s get into the details of how crop rotation offers all of the benefits mentioned above.

Prevents Nutrient Deficiency

Growing plants repeatedly in the same spot can create a deficiency of certain nutrients in the soil. For instance, if you grow members of the nightshade family (tomato, peppers, potato, and eggplant) in a portion of your home garden for two to three years straight, you will notice a gradual decline in their yield. This is because the nightshade family is a nitrogen sucker; it will dry up soil’s nitrogen reserves within a few seasons. Nitrogen deficiency will affect their growth and productivity.

But rotating nightshade varieties with another plant family will help maintain nutrient balance of the soil. This will allow the soil to recover its nitrogen stores before the next batch of nightshade is planted. You can alternate nightshade plants with cruciferous plants, onions, and radishes all of which are phosphorous absorbers. Using a leguminous cover crop before planting nightshades will produce even better results. This will replenish nitrogen in the soil before a nightshade variety is planted.

Controls Plant Diseases and Pests

As mentioned before, plant pathogens and pests are attracted to particular plants only. This depends on the plant physiology and the type of carbohydrates and exudates that these plants produce. And even if you cut down a diseased plant, plant pathogens reside in the soil, waiting to attack the moment that plant regrows. So how can crop rotation help here?

Well, switching the location of that particular plant with another plant variety will clear those pathogens from the soil because they will either starve or move to another spot.

Builds Soil Biodiversity and OM

Soils which are subjected to crop rotation are found to have higher microbial biomass and microbial activity compared to other agricultural soils. This is probably because planting a variety of plants provides the soil with a variety of crop residues, each of which has a different C:N and a different elemental composition. Their breakdown and decomposition add a rich OM to the soil and release a variety of mineral elements, while also promoting a diversity of soil organisms. For instance, herbs like thyme, fennel, and mint attract beneficial insects while leguminous plants colonize rhizobacteria in the soil. Planting these varieties periodically will help to improve that succession level of soil a lot quicker than it would normally do in the absence of crop rotation.

Aerates the Soil

Soils where crop rotation is implemented are found to have a better aeration rate than normal soils. Such soils have a reduced bulk density (a measure of how closed particles are packed). Reduced bulk density means that these soils allow roots to grow freely without facing any resistance. Roots are able to explore more areas and have better access to nutrients and water. Soils with regular crop rotations have larger pore sizes which means that they are able to hold more water and allow a better gaseous exchange to the plants (Grains Research and Development Corporation, 2009).

Plants like daikon radishes, cereal rye, carrots, turnips, potatoes, and sunflowers are known to offer biological tillage as they have a deep root system that tills the subsoil and improves soil structure. Planting a few of these plants regularly in your soil allows you to provide natural tillage in your land without disturbing soil organisms.

The Magic of Sheet Mulching

The importance of mulching in farming can never be overstated. It is the essence of sustainable agriculture and an easy way for you to help the soil by returning the nutrients back to it. Mulching involves covering the soil with a layer of organic or synthetic material to assist the soil by enhancing the water retention capacity, adding OM, and controlling the growth of weeds.

I know this is a slight shift from our “letting nature do its magic” policy, but this technique doesn’t interrupt the processes going on in the soil; we are simply providing a layer of goodies to assist the process. In fact, mulching occurs in natural ecosystems too. The forest canopy adds an abundance of leaves, bark, fruits, and animal excrement on the forest floor which provides a mulching effect.

Mulching produces many positive effects on your soil::

Humus Production

Decomposition of the components of mulch gradually adds to the OM of the soil. Humus which is an essential component of topsoil can easily be improved through mulching.

Water Retention

A layer of mulch acts as insulation between soil and the atmosphere. This helps the soil retain moisture for a longer duration than it would normally do without a sheet of mulch. Mulch also provides a cushioning effect against rain thus preventing soil loss through erosion and runoff.

Soil Protection

Mulch reduces soil compaction by adding OM and moisture into the soil and protecting it from physical pressures that might cause compaction. The addition of OM improves the structure of soil aggregates and improves pore size.

Weed Suppression

The seeds of most weeds lie dormant in the soil waiting for their perfect chance to germinate. Sunlight provides them with this perfect opportunity, and with a little bit of moisture, they germinate (Muntean, 2021). This means that by simply limiting their sun exposure, we can limit the weeds' growth in our soil. Mulch performs this function perfectly by covering the cultivated land entirely with a dense layer of organic matter. In the absence of sunlight, most fungal cysts and seeds are sent into a state of dormancy or eliminated completely thus putting an end to the "weed problem."

Promotion of Soil-Beneficial Organisms

The rich layer of humus that mulch adds into the soil helps improve the diversity of plant-beneficial organisms including rhizobacteria, protozoa, earthworms, and beetles.

Maintenance of Soil Temperature

Mulch resists rapid temperature fluctuations in soil temperature by providing insulation between soil and the atmosphere. This feature of mulch is extremely useful for plants growing in cold environments where shallow-rooted plants can incur freeze damage. It is for this reason that mulching is an integral part of farming in cold regions.

Some people feel like mulching takes a lot of effort and time, but I think that it saves you a lot more time and effort than you'd otherwise spend on watering, weeding, and fertilizing your crops. In my opinion, mulch is a magic sheet that conceals all of your soil problems and allows you to enjoy fertile soil.

Mulching is rapidly gaining popularity among gardeners. Production of mulches has seen a rapid increase in the last decade, and currently, there is a huge variety of commercially available mulches that offer multiple crop benefits. However, some people like to generate their own mulches through composting methods. And I strongly advocate for creating your own mulch that is optimized according to your soil's requirements. This ultimately improves the health and productivity of plants that you are growing.

6

COMPOSTING FOR MULTIPLE BENEFITS

Do you know that an average American person generates 4.5 pounds of waste on a daily basis? This doesn't sound like much but this small amount mounds to 1,600 pounds per year. Referring to the recycling capacity that we currently have, 34% of this gets recycled, 13% is incinerated, and the remaining 53% ends up in landfills—an estimated 136 million tons, which is *not* a small amount. This means that each year, we are sending 22% of our food to landfills (Addison County, 2019).

With the world hunger index hitting an all-time high and the ecosystems being destroyed at a rapid pace, we just cannot afford to waste organic resources like we are currently doing. You'd think that sending the food to the landfills is good because it returns the nutrients back to the soil, but that's not how landfills work. Food that reaches landfills doesn't add anything good to the ecosystem. In landfills, the waste decomposes anaerobically only to release greenhouse gasses into the atmosphere. Composting, on the other hand, is an excellent alternative to landfilling. It follows the natural decomposition mechanism that occurs in the presence of oxygen and produces nutrient-rich compost that can be applied to the soil to improve its fertility. It attracts plant-loving soil organisms and limits the population of harmful ones. Composting organic waste is also an excellent way to cut down on the emission of greenhouse gasses.

Sacramento County in California is an excellent example for organic waste management. Senate Bill 1383 mandates the residents to sort out their organic waste from the rest of the garbage. This organic waste is treated separately and later turned into compost (Sacramento County, 2022).

The Basics of Composting

Composting may seem like a simple gardening technique, but it is a lot more complex than that. Recall the diversity of the soil food web; it is the exact diversity of macro and microorganisms that rules the world of composting.

Merriam-Webster defines compost as "a mixture consisting of decayed organic matter that can be used to fertilize the soil." Compost consists of a mixture of humified organic matter and mineralized organic substances, both of which are produced under aerobic conditions. A combination of these two components makes compost the best food for soil. Nutrients in compost exist in their simplest form ready to be consumed by the plant.

- The carbohydrates in compost are transitioned from their complex insoluble state to a

soluble form that is easily dissolved in soil solutions and absorbed by microorganisms or plant root hairs.
- The proteins are decomposed into smaller amino acids which then catabolize to ammonium compounds. Their final conversion produces ammonia or free nitrogen that can escape into the atmosphere or re-enter the nitrogen cycle once mixed with the soil.

In relation to the wide variety of components in the organic residues and composting methods available, there are several composting systems which we'll discuss later.

The world of composting is dominated by microorganisms like bacteria, fungi, and actinomycetes. Decomposition begins as soon as the basic conditions for microbial growth are met. Carbon, nitrogen, oxygen, moisture, and a hospitable environment are the most essential requirements for microbial activity to initiate. Worms and beetles are not present when the composting starts, but they gradually find their way into the composting sites.

The following are common living organisms that you may find in a compost bin:

- Bacteria—carry out most of the decomposition and generate heat while they do so.
- Fungi—decompose the hard carbohydrate structures present in yard clippings and plant waste. They can also degrade the components that have extreme pH ranges.
- Actinomycetes—these are special types of bacteria that have filamentous bodies. They are extremely good at decomposing hard parts of the plants such as the bark and stems.
- Earthworms—carry out the churning of a compost pile, which assists the bacteria in decomposition.
- Millipedes, beetles, slugs, snails, and mites—break the organic matter into smaller pieces to speed up the decomposition process.
- Centipedes, beetles, and springtails—add nutrients to the compost pile and keep the population of primary decomposers under check.

Efficacy of Composting

The following factors determine the efficacy of composting:

Carbon to Nitrogen Ratio

One general rule that governs the efficacy of composting is the ratio of carbon to nitrogen (C:N) that exists in a compost pile. This ratio determines the ease with which microbes decompose the compost pile. Carbon in the form of carbohydrates acts as the primary energy source for the microbes while nitrogen (in proteins) acts as the building block for their proteins and nucleic acids. A 30:1 is considered the ideal C:N ratio for composting. The amount of nitrogen is always kept low otherwise nitrogenous compounds produce an excess of ammonia and nitrogen gas that creates a foul odor in the composting pile. At a low N-concentration, bacteria doesn't rush through their lifecycle. Instead, bacteria work their way gradually through the compost pile, thus producing a well-decomposed, earthly-smelling compost.

Aeration

Since the whole process of composting is operated anaerobically, aeration is the most important factor that can ensure the optimum activity of microorganisms at all times. To ensure that the composting sites/containers need to be well-ventilated. Aeration is also essential to maintain suitable levels of carbon dioxide and moisture in the compost pile. Continuous dumping of organic residues on the top of the pile without properly aerating it can result in compaction.

Moisture

Since microorganisms don't have complex transport systems, they rely on water which acts as a medium for them to exchange nutrients, gasses, and energy with the atmosphere. Water plays the same role in a compost pile by allowing microorganisms to access nutrients stored in organic matter. This means that a certain concentration of moisture needs to be present in the compost pile at all times to ensure the optimum activity of microorganisms. A 40-60% moisture by weight is considered essential for optimum microorganism activity (Cornell Composting, 1996). An amount lower than that dries up the pile while anything more than that creates anaerobic conditions in the pile because water-clogged-pores leave no space for gaseous exchange.

Temperature

Temperature is a variable factor of composting. It fluctuates between different stages of composting according to bacterial requirements. The composting process is divided into the four stages below, each of which is characterized by a specific temperature range:

1. Mesophilic stage—this stage is characterized by an initial breakdown of organic residues to simpler sugars, proteins, and starches by mesophilic bacteria. Their production raises the temperature to 20–30 °C (68–86 °F). At the end of this stage, bacteria produce endospores. Endospores are the envelopes that allow them to withstand extreme temperatures and pH fluctuations during the next stage of composting. Mesophilic bacteria become active again when the temperature becomes suitable for them.
2. Thermophilic stage—this stage is controlled by thermophilic (heat-loving) bacteria that raise the temperature of compost to 50–60 °C (122–140 °F). They decompose sugars completely to their constituents, degrade the proteins to amino acids, and begin the breakdown of cellulose and other hard residues.
3. Curing stage—the mesophilic bacteria hiding in endospores become active again as the temperature returns to 40–45°C (104–113 °F). At this point, carbohydrates and proteins are completely decomposed and only hard residues like cellulose and lignin remain. Fungi and actinomycetes become active to facilitate the breakdown of these molecules. An increasing population of earthworms and other insects assists in the breakdown of organic matter.
4. Maturation stage—the temperature lowers to 20–30°C (68–86 °F). By this time, decomposition is almost complete. The carbonaceous compounds condense while other nutrient compounds undergo polymerization to give the compost a crispy, crumbly texture.

Temperature fluctuations occur smoothly in a compost bin as long as all the other components are provided. However, during the winter, compost bins/sites need to be insulated to maintain a steady temperature of the compost.

pH

Initially, the pH of the compost is set by the type of materials that are fed into the compost bin but as soon as the microbial activity initiates, pH changes according to the types of compounds that microbes are producing. This pH can vary between 4.5–8.5. Microbes are extremely sensitive to pH; their growth is directly dependent on pH. Bacteria usually thrive between a pH range of 6.0–7.5, while fungi love a range of 5.5-8.0.

Residue Size

Particle size determines how easily microbes degrade an organic residue. Smaller particles are easier to degrade, causing their decomposition to occur more rapidly. They are also well aerated and able to retain more moisture in between their surfaces. Therefore, shredding the materials before adding them to the compost pile is always a good idea. An optimum size of two inches or less in the largest dimension for efficient composting (*Compost Fundamentals: Compost Needs - Particle Size*, n.d.).

Size of the Compost Pile

The size and volume of the compost pile is important because it affects the temperature regulation, aeration, and moisture retention properties of compost systems.

Large-sized compost piles lose their heat and moisture too quickly to the atmosphere plus excessive aeration interrupts the activity of bacteria and actinomycetes. On the other hand, extremely small compost bins heat up too quickly, plus lack of aeration and high moisture retention can spur anaerobic activity within them. To avoid all of these issues, a moderate-sized compost pile is recommended. An ideal composting bin should be three to five square feet in size (Fact Sheet Compost Bin, n.d.).

There are three basic types of compost based on the type of biology that they promote:

- bacterial composts
- fungal composts
- balanced composts

Bacterial or Alkaline Composts

Bacterial or alkaline composts contain the material that naturally favors bacterial growth. These composts get turned regularly, which nourishes aerobic bacteria but hinders the fungal population because of continuous disturbance. The acids that these aerobic bacteria produce are rapidly oxidized in an abundance of oxygen to form alkaline products. This turns the environment of bacterial composts slightly alkaline. A high oxidation rate in bacterial composts means that nitrogen is rapidly converted into nitrates. When added to the soil, these nitrates may spur early growth but they are soon leached out of the soil.

These composts can be turned into fungal composts by adding fungal-promoting substances and lowering the frequency of aeration.

Fungal or Acidic Composts

Fungal composts proliferate when complex carbohydrates like lignin and chitin are fed into the compost pile. These composts are highly nutritious but equally hard to obtain. Aside from the nutrients that these composts provide to the soil, the fungal population alone provides several benefits to the growing plants. The acidic pH of fungal composts makes them extremely stable which means that they release nutrients slowly into the soil according to the plants' requirements.

Balanced or Neutral Composts

Balanced composts have almost equal populations of bacteria and fungi which means that their pH is neither acidic nor basic; it lies between 6.5–7.0. To obtain these composts, the aeration just needs to reach a certain point so that anaerobic conditions are avoided, and at the same time, compost disturbance should be minimal so as to promote fungal growth.

Most of the composting methods out there try to procure neutral compost due to their wide applicability. Most farmers prefer neutral composts because these composts act as a buffer between their soil and atmosphere. Neutral compost can be applied to all soil types, unless the soil is intended for growing special crops that require acidic or alkaline pH.

How to Obtain the Perfect C:N for Your Compost?

Remember the ideal 30:1 carbon-to-nitrogen ratio that we talked about? How can you obtain that ratio when you are composting at home? Some would say that you absolutely don't need to worry about this ratio, and instead, you can purchase compost from a nearby store according to your requirements. But I believe that you should be aware of everything that you are feeding to your soil, and because of that, you should prepare your own compost. Of course, compost-producing factories provide all of that information regarding the value of C:N, moisture content, pH, and microorganism diversity. But do you think that is enough information or that the information is *exact*? No, absolutely not!

Most factories list generalized values that they calculate by drying out the compost and performing lab tests once the compost is prepared. Also, these factories don't use a variety of organic mass when preparing the compost. On the other hand, you can prepare a perfect compost at home where you can include a wide variety of materials and obtain just the right C:N with minimal effort.

Look at the table below to decipher what some of the best ingredients for your compost preparation are, and what should never be included in a compost pile.

Materials/Ingredients	Description	Examples
Add these to the compost		
Browns	These include each and everything of plant origin that has turned brown either because it's dead, highly mature, or highly processed. These may also contain small amounts of cellulose and lignin. Plants that have gone to seed are also included in this category. Browns are extremely high in carbon which helps to add bulk. Their crisp nature helps to add air to the compost.	Dry leaves, sawdust, rice hulls, hay, straws, newspaper, and paper
Greens	Greens include all the vegetative parts of plants including leaves, stems, shoot buds, and roots. Since they are still in the growth phase, they contain a high population of bacteria, sugars, simple carbs, and small amounts of cellulose. Greens are rich in nitrogen. Food scraps are also included under greens.	Yard clippings, freshly-pulled weeds, shrub-trimming, recently -cut shoots and leaves, and food leftovers
Lignified Materials	These lignified substances are extremely high in carbon content and have negligible moisture content but these exact properties make them the best carbon source for plants as they release nutrients gradually to the soil while also improving their water drainage capacity.	Wood chips, sticks, corn stalks, cobs, seed coats, lignified branches, logs, hardwood and softwood bark, douglas fir bark, and pine needles
Fruits, Flowers, Seeds	Both flowers and fruits are rich sources of nitrogen and phosphorus, plus they harbor a wide variety of microbial content which is good for the compost. Their high sugar content makes their decomposition easier. Seeds, however small, are extremely rich in nitrogen because they need to initiate plants' growth.	Apple cores, fruit peels, vegetable tops (including that of onion, turnip, carrot, radish, beetroot, and garlic), naked seeds, nuts, and coffee grounds

Animal Waste	Animal manure is an important ingredient of composts. In fact, it is the single most important contributor of composts produced on most farms and ranches. All forms of animal waste are rich in nitrogen and therefore a crucial ingredient for compost preparation, but ruminant manures are most commonly used since they are easily available. Carcasses of small animals, spilled animal feed, feathers, and poultry litter can also be added to the compost pile.	Bird droppings, feathers, animal excrement, blood, urine, dung, fish skin and bones
Human Waste	The question of adding humanure to the compost piles is often met with conflicting views. Although it is *totally* compostable, there are several issues associated with the handling of humanure. However, the proponents of humanure composting suggest that with specially constructed toilets, this rich source of nutrients can be turned into compost. Besides humanure, you can also compost human nails and hair. These may take several years to decompose completely but they can slowly add nitrogen and carbon into the soil.	Human feces, human urine, toenails, fingernails, and hair

DO NOT ADD THE FOLLOWING TO COMPOST PILES		
Fats and Oils	You know oil and water don't mix, and you also know that water is the most important component of composting systems. Microorganisms use water as a medium during the decomposition process, and the addition of oil or fats can meddle with this medium. Anything that's covered in fats will resist decomposition. So, you need to steer clear of all forms of fats and oils including the items that contain a high proportion of oil/fat.	Cooking oil, lard, canola oils, butter, fish oil, baked items, and fried foods
Meat	Meat is perfectly degradable, but adding it to your compost pile will attract unwanted pests to your compost pile, and you clearly don't want that to happen.	Beef, mutton, pork, chicken
Dairy	The same reasons apply to dairy products; they contain fats, they attract unwanted pests, and they produce foul odors.	Milk, butter, cheese, cream, yogurt, whey, and casein
Items With Acidic pH	You know bacteria (especially mesophilic ones) are sensitive to acidic pH, so adding acidic ingredients to the pile will affect bacterial populations. Therefore, adding acidic items to the pile is not a good option.	Citrus fruits, pickles and vinegar
Highly-Processed Wood	Untreated wood is fine, but treated wood is not a good option for compost piles. Chemicals present in such woody items can negatively impact the chemistry of compost piles.	Treated timber
Teabags and Coffee Pods	It's okay to compost coffee grounds and tea leaves, but throwing them along with their packaging is not acceptable. Normally, teabags and coffee pods are made of nylon fibers or PET plastic, which are not easily degradable and create problems for a compost pile.	
Manure from animals that take antibiotics and dewormers	Manure from these animals may contain compounds that can be toxic to microbes present in the compost pile, thus lowering their productivity. This applies to humanure too.	

Composting Systems

Based on the composting conditions, composting can be divided into two broad categories i.e., hot and cold composting. Each of these composting systems is equally effective yet has its pros and cons.

Hot Compost

Hot compost is often referred to as Berkeley compost or aerated compost. Hot composting offers an easy quick recipe to obtain a nutrient-rich soil amendment that is rich in carbon, nitrogen, and other humic substances. The factor that makes this composting system "quick" and "hot" is the low C:N. Presence of high nitrogen content promotes the rapid growth of thermophilic bacteria, turning the compost pile into a finished product within two to three months. Components of a perfect hot compost are

- 30–33% carbon-rich browns
- 30–33% nitrogen-rich greens
- 30–33% of another nitrogen-rich material; this could be animal manure or a green (Powers, 2022g, p. 165)

High temperature in this composting system serves a dual purpose. It boosts the activity of "good" bacteria while finishing off all the "bad guys," including pathogenic microbes (that might be present on diseased plants) and weed seeds. Therefore the final product you get through this composting system is not only rich in nutrients but also free of harmful entities.

That's all good, but under what conditions can you brew a good-quality "hot compost"?

To start the decomposition process, the initial ratio between greens and browns is set at 1:1. The pile should sit for four days to raise its temperature and build moisture equally within the pile (Pleasant, 2016). After the first four days, the pile is aerated every two to three days (for two weeks) while maintaining its temperature between 55–63 °C (130–140 °F). Once the thermophilic stage is complete, the compost is aerated and mixed for a few more days in order to cure it to reach its final form (Pleasant, 2016).

Since everything in the hot compost is running on a tight schedule, you also need to be vigilant during the process; leaving a hot compost unattended can ruin the whole set-up. Hot compost piles that are left unturned for too long can combust spontaneously due to the accumulation of methane and alcohol. Therefore, hot composts require regular aeration and turning, constant temperature check-ups, and frequent carbon add-ons (in case the process is going too fast or your compost pile is shrinking due to the rapid formation of nitrates). But all of this effort will pay off once you obtain rich, earthly compost.

Cold Compost

I know, you are loving the idea of hot composting so far; it's quick and requires a one-time prep. You put every ingredient in the bin, supervise the process for a few months, and, voilà! You have your perfect compost. But even the slightest mistake in the preparation of the compost pile and later during the process can ruin your final product, especially if you are new to composting. Hot composting can be labor-intensive due to the frequent aeration requirements. To side-step these issues, cold composting or moldering is a great option. It's not high-maintenance and it can easily cover up your minor composting mistakes. In cold composts, fermentation by anaerobic bacteria is the primary driver of the whole process.

In contrast to hot compost, this method is a slow process that usually takes three to four months to complete. It doesn't involve a single preparation; you can add different components to the pile throughout the process. Unlike hot composting, the efficiency and quality of cold compost are dependent on various factors including the composition of the pile, its location, the surrounding environment, soil biology, and moisture. Cold compost is governed by anaerobic bacteria and, therefore, smells like rotten eggs.

To construct a cold compost, you will require a small pit or a damp spot where you can keep your composting pile for a long time. You can construct a perimeter around that area to keep your pile together. Then, put all of your ingredients in the pile and cover it with a lid or a tarp to retain moisture and keep pests away. You can leave your moldering pile for at least three months before the compost is ready for use.

Hot or Berkeley Compost	Cold or Moldering Compost
It's fast	It's slow
It requires a single large preparation at the start	It can work with any pile size, and more ingredients can be added along the way
It's aerobic	It's anaerobic
It's high maintenance	It requires minimal maintenance
Heat is the primary driving force behind hot compost.	Fermentation is the primary driving force in cold compost.

EM® and Bokashi

EM®(effective microorganisms) is a liquid soil amendment that is enriched with eighty different soil-beneficial bacteria and fungi along with sugar and lactic acid, all of which help in boosting the decomposition process of organic material present in the soil. This potent combination of probiotics boosts the transition of the dead, rotting organic matter into plant-accessible nutrients and minerals. Not only that, but it also boosts carbon and nitrogen uptake in plants. The nitrogen-fixing ability of soil microorganisms is also improved because of this EM® mixture.

EM® is a trademarked product that is sold commercially on the following website:

https://www.teraganix.com/products/em-1-microbial-inoculant-soil-amendment (Teraganix Holdings, 2021)

This is the site that sells the original formulation of EM® (as EM-1®) which was first created by Japanese horticulturist, Dr. Teruo Higa, in the 1970s. Several other sites are selling the same product under other names.

How Does EM® Work?

Since EM® is in liquid form, the microorganisms in it are able to access the targeted site and perform their role through fermentation. In the soil, these bacteria, yeast, actinomycetes, and filamentous fungi grow rapidly in the presence of lactic acid and sugars. These rapidly growing populations of microorganisms then help improve soil texture and fertility profile by breaking down the organic residues into constituent elements and making them accessible to the plants. On compost piles, EM® application is known to boost the degradation of organic materials by enhancing microorganism activity.

EM® is not just a simple soil amendment and has several other uses. It can be used

- as a household cleaner.
- to clean waste after catastrophic events like earthquakes, and tornadoes.
- to kill pathogenic bacteria species.
- as a foliar spray before the flowering of plants.
- as a pest repellant.
- to remove odor from the septic tank.
- to improve animal health by adding it to their feed.

Getting EM® Ready

There are several options available when it comes to getting EM® ready for use:

1. You can order a prepared concoction directly from their website.
2. You can replenish your supply of EM® from the small amount that you already have.
3. You can prepare your own EM® liquid.

Prepared EM® can be applied directly wherever required.

To replenish your supply of EM® from small amounts of mother culture, you'll need to mix

- one part EM®
- one part molasses
- twenty parts water

You'll then have to leave the mixture to ferment for a month in an airtight container, and by the end of that period, you'll have 20 times more EM® than you initially had. Be aware as you grow your own culture, it will off gas CO2, and if the the container you are growing your culture in does not allow for expansion from off gassing then the container could burst. I prefer to recycle an old plastic jug or water bottle to culture my EM®. On a larger scale you can use a 55gal fermentation barrel.

Now, if you want to compose your own EM®, all you need to do is mix green waste like vegetable waste or fruit peels with bran and brown sugar in a container with a tight-fitting lid. Bacteria on vegetables and fruits will rapidly consume the bran and sugar, and their populations will start to grow. Keep this mixture tightly closed for a week and stir occasionally from day to day. This fermenting mixture will soon start to produce liquid waste of which you will have to collect in a container and allow it to ferment even more by adding more bran and brown sugar. Initially, you'll have a composition of EM-1® but it will transition to EM-2®, EM-3®, and EM-4® upon each successive fermentation.

You can apply this homemade EM® as frequently as needed. Some people like to apply small doses during the growing season to improve plant growth, but some prefer single application during the start of spring and fall seasons. To facilitate flowering and fruiting, EM® is also applied through foliar sprays. To increase the efficiency of composting, one part EM® is mixed with 99 parts water and applied to the surface of compost piles.

Bokashi Composting

Put simply, bokashi composting is just an extension of the EM® concept. It was developed by Dr. Teruo Higa in the 1980s to direct the utility of EM® toward efficient compost production. Bokashi composting is unique in that it requires 10–14 days for completion. Also, it can break down a few components (like meat and dairy) that are usually considered bad in other composting methods. The products obtained through this method can find several uses in your farm:

- The ferment can be dug directly into the soil.
- The nutrient and microbe-rich bokashi mixture can be applied to another composting pile to improve its composting efficiency.
- The compost tea (liquid ferment produced during bokashi composting) can be applied to garden plants (in 1:10 dilution) to improve their growth and productivity.

Preparing Bokashi Compost

Bokashi composting requires two special ingredients:

- EM®—store bought or homemade
- A bokashi bucket—a container with an air-tight cover and a tap at the bottom to drain-off compost tea.

The procedure involves mixing different organic materials (greens, meat, and dairy) with a bokashi inoculant in a bokashi bucket and fermenting it for several days. Now, bokashi inoculant is just a fancy term for activated EM® meaning that it is a mixture of bran, molasses, and effective microorganisms. Bran can also be replaced with wheat germ and sawdust. Molasses and bran help to activate the microorganisms that are lying dormant in EM®, and then, this potent mixture can ferment the scraps present in the bucket.

Similar to EM®, you have three options with bokashi composting:

1. You can purchase a bokashi kit from a garden store. These kits contain all ingredients complete with step-by-step instructions for composting.
2. You can buy an EM® and bokashi bucket and prepare a bokashi compost of your own.
3. You can prepare everything at home including EM® preparation and re-purposing of an air-tight container to a bokashi bucket.

Once the process starts, all you need to do is drain bokashi tea (through the tap) regularly from your bucket and not disturb the rest of the set-up, otherwise the efficiency of fermentation will be compromised. Remember, the reason for keeping the container air-tight is to prevent the development of aerobic conditions in the bucket. Fermentation is an anaerobic process that must be kept free of oxygen.

Although bokashi composting is an excellent method to reduce kitchen waste to nutrient-rich ferment, yet it cannot be applied directly to the soil as mulch; you can either bury it in your garden or add it to another one of your traditional composts.

Vermicomposting

Recall the functions that soil organisms like shredders and grazers perform for the soil. Bioturbation mixes organic matter with the soil, aerates it, and improves the gaseous exchange property of the soil. Decomposition and nutrient cycling break down the organic matter and release the nutrients in a plant-ready form.

The concept of vermicomposting is based on these exact functions. All the composting is carried out by worms; they break down the organic material into smaller pieces, aerate the pile, and mix it up with the humic content, and finally, they digest the organic matter to release nutrients and minerals directly into the soil.

I believe that vermicomposting is the easiest composting method because

- it is low-maintenance. You'd think that maintaining a bin full of worms would be difficult, but it's not; worms are simple, self-sufficient organisms.
- it doesn't require frequent aeration/mixing; worms do that too.
- it is one of the most efficient composting methods.
- this decomposition process is not dependent on heat.

Vermicomposting results in the production of worm castings which are the most enriched form of soil conditioner. Basically, it's *worm poop* that worms produce after consuming and digesting the materials in the compost pile. The addition of vermicompost to the soil can immediately boost its nutrient availability, aeration, and soil structure. Also, additional worms can improve the succession level of the soil.

Worms Used in Vermicomposting

There are no strict rules about the selection of worms for vermicomposting. However, according to Groffman (2007) there are some studies that show worms to be invasive and damaging to the OM present on the forest floor. Compared to the indigenous worm species, non-native species have been found more damaging to the soils. For this reason, vermicomposting near forests is not a good idea. Also, it is always best to try to use an indigenous worm species when possible. In recent years, a wide variety of worms have been bred for this large-scale vermicomposting. Still, the two pioneer worms for vermicomposting are

- *Eisenia foetida*–these go by the name of red wrigglers and are quite abundant in the topsoil. They are also used as fish bait.
- *Lumbricus rubellus*–these are commonly known as night crawlers and are abundantly found in the deep layers of soil.

These worms are able to thrive at a wide range of pH, temperature, and moisture levels. They perform very well between a temperature range of 13–30 °C (55.4–86 °F), but they can also survive at temperatures below 13 °C (55.4 °F) or above 37 °C (98.6 °F) (Sherman, 2021).

However, to preserve their optimal activity, provision of a cooling system in summer and an insulating system in winter is recommended. As for the pH, they can grow over a pH range of five to eight (“Soil Quality Indicators Earthworms,” n.d.). High moisture and ventilation are also important for their uninterrupted growth.

Types of Vermicomposting Systems

Another thing that makes vermicomposting easy is that it can be done in a variety of ways. Overall, there are three vermicomposting systems:

- bed composting
- windrow composting
- bin composting

Bed vermicomposting is done by placing worm-containing beds right into the soil. These beds are formed by placing shredded cardboard, organic waste, and worms right into a garden bed.

Windrow vermicomposting is often done by large governmental organizations that aim to deal with municipal organic waste or large food processing companies or hotels. Organic waste is arranged in long piles which are turned often to provide aeration.

Bin composting is the most popular way of vermicomposting. It allows you more control over the composting conditions. It is easy to handle and a great option for those who want to get rid of kitchen scraps. So, let's see how you can construct your bin vermicomposter at home!

1. First you need to select a bin. It doesn't need to be a fancy one. You can repurpose any plastic box or wooden container for this purpose. There are no specific requirements regarding the volume of the container; it can be anything between 1–55 gallons. Make sure you select a dark-colored container because worms like darkness. Also, the container should have a lid to protect the worms from rain and animals. You can add a few holes in the sides (near the top) of the container to allow ventilation. There is no need to add drainage holes at the bottom unless you maintain sufficient levels of moisture in the container without allowing rainwater to seep in.
2. Next you have to select a location for your compost bin. An ideal place should be shaded and have a temperature between 13–30 °C (55.4–86 °F). Also, it should be a well-ventilated spot. In summer, you can shift its location and water it more often if you feel that temperature is not being regulated very well. In winter, however, you can consider moving your bin to your garage or shed, or simply cover your bin with fleece to insulate it from the outside environment.
3. Once the bin has been placed in a perfect spot, you need to prepare damp bedding for your compost bin. To prepare an ideal space for the worms before you place them in, you can start by putting some sandy soil and wet shredded newspaper in it. I don't recommend putting clay soil in it because it is compacted and can create aeration issues. Coco coir, shredded cardboard, dry leaves, and straw are also great options. All of these contents shouldn't be soggy when you put them in; we only want a 60% moisture level in the bin. Bedding is essentially the "browns" of this composting method. It provides the carbon source that counters the effect of nitrogen present in

the organic material added to the soil. You can continue adding more bedding during the process.

4. Now it's time to add worms to your bin. You can get these worms easily from a worm farm or a fishing supplies store. The question is: How many worms should you put in your composter? Well, that depends on the size of your bin. For a 15–30 gallon bin, I would recommend adding 500–1,000 worms. For 35–50 gallons, 1,000–2,000 worms will be enough. In the presence of sufficient food and a favorable environment, the worm population will double within three months, so you won’t need to add more worms.
5. Add a little food for them to energize before you actually start the composting process. To prevent them from escaping the bin, you can cover them with a few damp newspapers.
6. Notice their activity for at least one week and determine whether they adjust to their new “home” or not. If not, then there must be something wrong with the conditions in the bin. Recheck the ventilation, moisture, and temperature. Also, check the pH of the bedding and the food, and then adjust it according to the pH requirements of the worms.
7. Once you have got a complete vermicomposting system, you can start adding organic material to it. Since this system is reliant upon worms only, you should only add the things that they really like. They really like fruit and vegetable scraps, tea leaves, coffee grounds, fresh leaves, and yard trimmings. Never add a food item that can alter the pH of the composting. To determine the daily food requirements of your worms consider the fact that they can eat their body weight per day. So theoretically, if you have a current weight of two pounds (of worms), you could feed them two pounds of waste per day.
8. As soon as you feel that your worms are performing well and that they have produced enough worm castings, you can start to harvest them. But first, you have to divert the worms to one side of the bin. To do that, add food scraps to one side of the bin, all or most of the worms will move there and you can scoop out the worm casting easily out of the bin.

Johnson Su “BEAM” Bioreactor

Biologically Enhanced Agricultural Management or “BEAM” is a relatively new concept that has been developed by Dr. David Johnson and his wife Su Johnson. It offers a bunch of benefits for soil and plants in almost all environments. BEAM material is produced in a special kind of bioreactor called a “BEAM bioreactor” that houses a static pile and provides it with aerobic conditions to produce a fungal-dominant, nutrient-rich compost. In fact, bioreactor-based composting is the highlight of this concept. In contrast to mass-producing bioreactors that are used commercially, a BEAM bioreactor allows the biomass to decompose thoroughly over a long time (one year or more). And unlike the home-composting system, which often smells and attracts pests, a BEAM bioreactor is a closed system that breeds microbes in a completely aerobic environment that prevents the development of foul odors.

BEAM material is known to harbor 400–500 types of fungal and 2,700 types of bacteria species (Beam compost, n.d.). This wide variety of bacteria and fungi when applied to the plants ensures that the most favorable species colonize the plants’ roots so as to improve their growth and productivity. You can construct a BEAM bioreactor at home or order the needed material directly from the online store using the link below:

https://beamcompost.com/ (Beam compost, n.d.)

BEAM material has wide applicability; it can be mixed with the soil before planting, it can be applied as a mulch, it can be made into a compost tea, and it can be used as a seed coat before sowing. Quantities as small as two pounds per acre can produce miraculous effects for plants. These effects include

- increased carbon sequestration in soil
- increased nutrient availability
- improved water infiltration
- increased water retention capacity which can reduce plants' water requirements up to six times
- increased seed germination when applied to the seeds before sowing
- 50–100% increased crop yield
- decreased fertilizer requirement (Beam compost, n.d.)

Compost Teas

In the part about bokashi composting, I mentioned how the liquid part of the ferment (bokashi tea) can be applied directly to the soil as it is compositionally similar to the rest of the compost and offers several benefits to the plants. Just like that, compost tea is a broad term that we use for all kinds of composts that exist primarily as liquids. The term "compost tea" may be new but the concept is not. The same products have been used in the agriculture sector for several decades, only they were known by the names of fermented extracts, amended extracts, slurries, and compost steepages.

Personally, I am a huge fan of compost teas and there are several reasons for that. First, compost tea contains dissolved nutrients that can be absorbed readily by plants' roots. Second, they contain highly active bacterial populations, some of which may lie dormant in the solid compost. Last, compost tea is easy to apply on plants and plant parts; they can be added as soil drenches directly onto the soil, they can be used as foliar sprays on leaves and shoots, and they can be incorporated into the crop irrigation system.

There are several ways to obtain compost teas. You can

- drain the compost tea from a compost system that produces liberal amounts of liquid compost along with solid compost.
- dissolve a compost tea bag in water to extract microorganisms and soluble nutrients from it. Compost tea bags are easily available in garden supply stores.
- brew your own compost tea.

How To Brew Compost Tea?

Compost teas are broadly classified as aerated and non-aerated. Aerated compost teas are obtained through systems that feed oxygen continuously to the compost mixture. Contrastingly, non-aerated systems consist of static compost mixtures that are left to ferment anaerobically. For this reason, non-aerated compost teas are easy to make, but for aerated teas, you need to install a bubbler or agitator that could force air into the system. Let's see how this can be done.

To construct an aerating compost bin, you'll need a 6.5 gallon bucket with a lid, an aquarium pump with a hose, a T-valve, and a porous bag or sieve (to keep the solid compost separate for the compost tea). For starting culture, you'll need approximately five gallons of water and two to four cups of fine compost.

1. Add chlorine-free water to the bucket (rainwater is chlorine-free or you can add tap water and leave it overnight to remove chlorine from it).
2. Install an aerating system using an aquarium pump and T-valve and start aerating the water.
3. Put compost in the porous 400 micron bag and suspend it in the bucket.
4. Aerate the contents of the bucket continuously for 1–72 hours.
5. This will allow the content of the solid compost to mix in the water.
6. Drain the compost tea and filter it through a strainer or a cheesecloth to remove large residues that might be suspended in the tea.
7. Apply it immediately as foliar spray or as a soil drench.

Composts and compost teas are important components of sustainable agricultural practices. They can serve as an excellent addition to your soil; they can improve soil structure and improve plant health without having you till your soil. However, composting is a slow process and so it is best to start compost preparation long before it's actually required. This will give you sufficient time to perfect your compost before it is applied to the soil.

7

KOREAN NATURAL FARMING

All techniques and methods that we have covered so far can help you improve your soil health and your crop yield when used with traditional agricultural practices; but what if I tell you that we can completely revamp our agriculture to a new, sustainable, affordable and profitable farming method?

Korean Natural Farming (KNF) is the latest addition to the farming techniques that are gaining popularity due to its numerous agricultural, environmental and economical benefits. Unlike other recent practices that mainly focus on enhancing yields without paying much attention to what they feed the soil, KNF pays attention to the input that is given to the soil. The idea behind KNF is that soil health, and crop productivity can be enhanced by paying attention to the requirements of the "living soils." KNF collaborates with nature to detect what soil wants and how that can be provided without disrupting the natural processes that are going on in the soil. In short, this method is an easy way to achieve John Kemp's stages of plant health in real-time.

Like other agriculturists, farmers and gardeners, you must be fully aware of the importance of soil additives in determining your soil's productivity but you also know that these additives are not cheap. I believe that once you start applying these additives and fertilizers to your soil, there is no turning back; the soil becomes addicted to them. Lack of attention to soil's natural resources drastically lowers its productivity unless you supply it with liberal quantities of fertilizers/additives in every cropping season. KNF aims to put an end to this perpetual cycle of fertilizer application by encouraging farmers to rely on their indigenous resources to boost soil fertility.

What Is Korean Natural Farming?

The concept of KNF was developed by Dr. Cho Han Kyu in the 1960s in a bid to lower South Korea's dependence on chemical fertilizers. He focused on the reuse of farm waste products like indigenous microbes, wild plants, and compost to improve soil health. His ideas and methods were later popularized under KNF. Today, several countries are successfully implementing KNF in their local soils. Through KNF, farmers and gardeners try to create a closed loop of farm inputs and outputs, meaning that everything their farm requires is sourced from within the farm itself. Besides sourcing inputs directly from the farm, another important aspect of KNF is the timing of inputs. Dr. Cho has explained this idea through his "nutritive cycle theory," according to which plants need different nutrients during different stages of their growth (Frost, 2021). For instance, there is a preparation of water-soluble calcium (WS-CA or

WCA) that consists of toasted eggshells and vinegar. It is beneficial when applied to plants as they transition from the vegetative to the reproductive stage.

IMOs–Indigenous microorganisms

IMOs are an integral component of KNF. They are harvested from the soil, cultivated in large amounts, and reapplied at their previous location. Since they are the "indigenous" species, they are well-adapted to the soil. This eliminates the risk of losing the species because they are failing to adapt to their new environment, something that happens often in the case of commercially-prepared microbial inoculants. IMOs improve yields by addressing several aspects of plant health including nutrient availability, stress tolerance, and disease resistance.

Now, the collection and colonization of these IMOs don't require costly equipment or chemicals; everything is available on the farm (in most cases). In this process, steamed rice is placed in a wooden container which is then tightly covered with a paper towel. The container is then taken to a nearby forest and placed near a spot where fungal populations are present. To increase the chances of fungal growth, a few leaves and twigs covered in fungal mycelium are placed on top of the paper towel. Just within three to seven days, the rice becomes fully covered in fungal hyphae and other IMOs. This preparation is referred to as IMO-1. IMO-1 is then weighed and mixed with brown sugar which turns the microbes dormant for the time being (called IMO-2). This mixture is then mixed with a carbonaceous source and composted lightly to make IMO-3. In IMO-3, microbes exist in highly activated form. This form of IMO is then added to the soil and composted at low temperatures to form IMO-4. This is the form that can be applied directly to the plants or composted again to form IMO-5 (Frost, 2021). IMO-5 is the final form of IMOs which when applied to the soil, improves its nitrogen-retention capacity by increasing the fungal growth (which siphons freely available nitrogen in its mycelium).

Other KNF Inputs

Just like IMO (1-5), there are several other preparations that Dr. Cho collectively calls KNF inputs. All of these inputs are highly unique in their nutritive content, yet equally beneficial for plant health. They are beneficial for livestock too. More importantly, all of these inputs are prepared from locally-available materials. Let's have a look at the properties of each of these inputs.

LAB–Lactic Acid Bacteria

This KNF preparation consists of a culture of lactic acid bacteria which are anaerobic bacteria that convert carbohydrates into lactic acid and several other simpler metabolites.

This soil input is prepared using rice water which is first rested for a few days until it starts smelling sweet. It is then mixed with milk. Lactic acid bacteria ferment milk to produce curds and whey. Curds are removed and whey is strained to obtain a LAB-rich input for plants.

LAB solubilizes phosphate when applied to the soil in the 1:1,000 diluted form (Powers, 2022h, pp. 181–195). It can be used on animal bedding and chicken coops to rid them of the pungent ammonia smell. It can speed up the composting process by boosting the rate of fermentation in the compost piles. LAB can also be used as a rich soil inoculant and foliar spray when mixed with other KNF inputs.

LAB Preparation

Let's look at the ingredients and procedure for LAB preparation. For this preparation you’ll need

- a strainer
- glass jars
- breathable cloth
- rubber band
- rice
- water
- milk

Procedure

1. Soak rice in non-chlorinated water for 24 hours.
2. Strain rice water in a separate jar and cover it tightly with a breathable cloth and a rubber band to attract LAB. This will usually take a week or so.
3. Take one portion of this LAB-rich rice water and mix it with ten parts of organic milk.
4. For about five days, LAB will feed on the milk and separate the milk into two separate portions; a white curd on top and a cloudy LAB containing whey at the bottom of the jar.
5. Scoop out the curds from the top of the jar.
6. Store the remaining LAB-rich liquid in the refrigerator and use it as required.

OHN–Oriental Herbal Nutrient

This is a nutrient-rich input that is excellent for controlling the population of pests.

Preparation of this KNF input begins with the rehydration of some dry herbs like licorice, cinnamon, and angelica separately in wine and beer. Unrefined sugar is added as the process of fermentation begins. Then a few “wet” herbs like ginger and garlic are added to two separate jars and left for fermentation in the presence of unrefined sugar. All of these jars are covered with a breathable cloth and left for fermentation. After this period, vodka or any other 40% alcohol is added to each of these jars, and then they are covered with airtight lids. Following this, a 14-day fermentation period ensues, after which the liquid extract from each jar is drained into a separate jar to obtain an OHN extract.

It can be applied on aerial parts of the plants as 1:1,000 diluted foliar sprays (Powers, 2022h, pp. 181–195). This will help to control pest populations. It can be used on seeds to repel birds and insects. It can be utilized during the formation of IMO-3 and IMO-4 and it can be used to treat plants affected with mildews (powdery or mildew), necrosis, and rot.

FPJ–Fermented Plant Juice

This input is made using plant material from some of the most resilient plants. Unrefined sugar is added and the mixture is left in a fermentation jar for fermentation. Fermentation is allowed to occur for seven to eight days in a breathable container after which the liquid portion from it is drained-off into a new container. This liquid that was just prepared is known as FPJ and it can be utilized as a KNF input. Variants of FPJ can be obtained by using different kinds of plant materials. It is diluted to 1/1,000 of its initial concentration for plant application (Powers, 2022h, pp. 181–195).

FPJ is known to improve plant germination, especially in plants that are growing in cold environments. It can also help plants during their vegetative stages by increasing their nitrogen utilization.

FFJ–Fermented Fruit Juice

To prepare FFJ, ripened fruits are used. They are chopped and mixed with sugar to create a fermentation mix. This mix is then put in a fermentation jar, layered with more sugar, and covered with a breathable cloth. It is then fermented for several days until a thick fermented fruit juice is obtained.

1:1,000 diluted FFJ is applied to plants that are transitioning from the vegetative to the reproductive stage (Powers, 2022h, pp. 181–195). It is also beneficial for the reproductive growth of plants where it improves calcium uptake.

FAA–Fish Amino Acid

FFA input is made by fermenting fish scrap and fish bones which are layered with sugar and a little IMO-4. All of these ingredients are covered with a breathable cloth and fermented for three to six months until all of the solid content gets fermented.

FFA (in 1:1,000 dilution) can be used as a foliar spray for the vegetative growth of plants(Powers, 2022h, pp. 181–195). It can be used to repel pests like whitefly and mites. It is also a great compost initiator.

WCA–Water Soluble Calcium

This is made using coral sand and/or toasted eggshells. Both of these are mixed with vinegar and fermented for five to ten days or until the solid material gets fully fermented. This ferment is then strained and used as a foliar spray on fruiting plants.

WCAP–Water Soluble Calcium Phosphate

This KNF input is made using charred bones that are broken into small pieces. These bones are fermented in vinegar for 10–15 days. The ferment is then strained and stored for further usage. WCAP is a great foliar spray for plants during their vegetative growth and transition from the vegetative to the reproductive stage.

The purpose of sharing the ingredients and procedures involved in the preparation of these multi-purpose KNF inputs is to highlight the fact that *none* of these preparations require special ingredients or pieces of equipment since everything can be sourced from your house or farm. The method involved in their preparation is fermentation which might be slow and take time, especially during the winter season. On the bright side, it is an easy household procedure that will provide you with nutrient-rich farming inputs in any case.

KNF is a revolutionary farming technique that has the potential to change every aspect of agriculture for the better. There is not even a single aspect of KNF that is objectionable; it's sustainable, it's cheap, it's profitable, and it has no side effects. And the fun part is that you can involve all of your family members in to the process. You can involve your children in the preparation and application of KNF inputs while also explaining the science behind this farming technique.

8

YOUR STEP-BY-STEP ACTION PLAN

Every natural system has a self-replenishing feature that is responsible for maintaining its structural and functional integrity. But we have been meddling with these natural systems for a very long time, and I think it's time that we play an active role in restoring these systems back to their original form. Like other systems, soils around the world have also been suffering for a long time due to anthropogenic activities and they need to be restored.

You are now completely equipped with the basics of soil science. You know what's best for the soil and how you need to treat your soil to obtain long-lasting benefits. Fertilizers and other soil additives may provide temporary relief to your ailing soil but will worsen the problem in the long run. You will have to put in some solid effort and show some patience in order to reap long-term benefits from your soil.

Let's put together what we've learned so far.

Step 1: Check/Test Your Soil

A methodical approach to working with soil suggests that we test the soil to understand its nature, characteristic features, and shortcomings. Surely, an attempt to grow something in problematic soil will only be a waste of time and money.

Therefore, you will start off by performing the soil jar test. It's easy, simple, and can be done easily with household materials. The test will give you an insight into the texture and composition of your soil. Next, you'll establish the pH of the soil. That too can be done through a DIY test. You already know how important the pH of soil is. It determines the soil's nutrient profile, the kind of organisms that colonize the soil and the type of plants that grow in it. After that, you'll determine your soil's mineral profile using one of the soil testing kits, and if you still need to know the bioavailability of these minerals, you can get a plant sap analysis done for your soil.

Once you have screened the soil for its nutrient availability, you can use the DIY tests to determine the diversity of macro and microorganisms residing in the soil. This will help you determine the succession level of the soil. Lastly, you will perform a water infiltration and water availability test to determine the water situation in your locality.

Step 2: Adjust Your Soil

Having ideal soil conditions means that you'll spend less time and effort on making soil adjustments. However, if that's not the case, you need to use the information that you've collected so far to make informed decisions about soil remediation. This will include improving the composition, pH, mineral content, moisture content, and organismic diversity of the soil. You'll have to make these decisions according to the type of plants that you plan on growing.

For instance, if you found that your soil is predominantly sandy in nature, which doesn't rank high in soil fertility index and has water retention issues, you might be tempted to add more clay to it to deal with these issues. But before you do that, you should check whether the plants that you intend to grow are suited to sandy soil. What if you are planning to build a vegetable garden where you want to grow cucumbers, radishes, potatoes, and carrots? In that case, you won't need to amend your soil's composition. These plants grow well in sandy soil. Similarly, if you plan on growing a blueberry orchard and your soil has a slightly acidic pH, you don't need to adjust this pH, as it's already perfect for growing blueberries.

On the other hand, if you have noticed that your soil ranks low in its organic matter and mineral content, you can improve that using compost tea or a sheet of mulch (I hope you have selected a composting method by now and are already working on it). You can also use a cover crop to add more organic matter and nutrients to it. If your soil has a low succession level, an IMO preparation might help you with that.

Step 3: Aerate if in Dire Need

I am an advocate of no-till farming, but I do believe that tilling is the quickest method to improve soil aeration. Tilling damages soil structure only when done continuously over a long time. So, as long as you are in the initial stages of your farming journey, you can use tilling as a headstart for aeration purposes. But remember, it is only recommended if your soil is extremely compacted. You will know this through a soil infiltration test. If infiltration rates are extremely low, you can use a low-impact aeration tool to provide a little aeration to the soil structure.

A spike aerator is best for this purpose as it produces short-term decompaction on small yards. Moreover, it causes the least soil disruption. Compared to other aerators (like plug aerator) that remove soil during aeration, spike aerators have pointed tines that create holes in the soil without damaging the soil or removing it from the ground.

Step 4: Sheet Mulching to Build Soil Organic Matter

The next and most fun step in obtaining nutrient-rich healthy soil is sheet mulching. This involves layering the soil with numerous layers of organic materials, all of which decompose over time to add dark-colored organic matter to the soil. Besides adding organic matter, sheet mulching improves the water retention capacity of the land, prevents the growth of unwanted weeds, and builds more soil. In short, all of these layers prepare the land for the next plantation season. Winter is the best time to start sheet mulching since this allows sufficient time for the layers to compost and get mixed in with the soil.

Before you add the very first layer of mulch to your farm/yard, make sure the area is slightly wet. Moisture will kickstart the composting process by boosting the activity of microorganisms.

Layer 1—Chop and Drop

You will add the first layer by cutting down the vegetation that is present there and leaving it on the ground as the first layer of "greens." After that, you can aerate the land using a spike aerator or a pitchfork.

Layer 2—First Nitrogen-Rich Layer

Next, you will add a nitrogen-rich layer. Refer to the chart in Chapter 6 if you need a reminder of which components are good sources of nitrogen. You can add any one or two of these ingredients to the soil.

Layer 3—Wet Cardboards and Newspapers

Third layer of sheet mulch should consist of cardboards or newspapers. Once you have covered the designated area completely with cardboards or newspapers, you should water them to speed up their decomposition. This layer will prevent weeds and grasses from sprouting in your yard until the next planting season.

Layer 4—Second Nitrogen-Rich layer

Adding another layer of nitrogen-rich food scraps, fruits, and vegetables on top of the cardboard layer will attract macroorganisms and microorganisms to the site. These will eat away the cardboard layer and mix it with the layers below it.

Layer 5—A Layer of Browns

To add a layer of dead browns, you will lay an eight to ten inch-thick layer of dead leaves, grasses, and straws on top of the nitrogenous layer (Dostaler, 2022). This layer will add a bulk of OM to the soil. Adding lots of water to this layer will compact it and speed up its breakdown.

Layer 6—Compost

The layering that you have done till now will require time to decompose and mix with the soil especially if you do this in the fall. Then, at the beginning of spring, you can put a sixth layer consisting of good-quality compost (if you start composting in the fall, it will be ready in the spring). If you are layering in summer, you can put down compost soon after adding a layer of browns because the decomposition process occurs quickly at high temperatures.

You can use several options to add compost to your soil. You can use EM®, compost tea, or nitrogen-rich mulch.

Layer 7–Mulch

This last layer of mulch can be added after you have cultivated the soil. This layer will protect the layers beneath it, prevent erosion, hold moisture, and add more organic matter to the soil.

After this layer, you won’t need to till your soil anymore. At the beginning of every season, you’ll just remove what’s left of this layer, add a layer of compost, and replace the mulch back on top. Over time you’ll have the perfect organic soil for your plants.

Step 5: Choose Your Cover Crops

At the end of a season, if you plan to reward your soil with a bulk of OM, then cover crops are the way to go. A wide variety of cover crops is available for you to choose from. Besides adding OM, each of these crops offers several other benefits; some are nitrogen-fixers, some are good for producing livestock feed, some have pest-repelling properties, and some improve soil texture. You can choose a cover crop that is the best fit for your soil.

Step 6: Plan Crop Rotation

You are aware of the miracles of crop rotation. Now all you need to do is implement this rotation wisely. As mentioned earlier, you can do so in a number of ways. You can alter the location of main crop families, or you can plant a single crop family in each season. Important families are

- alliums—onions, garlic, and leeks.
- legumes—beans, peas, peanuts.
- brassicas—all cruciferous vegetables like broccoli, cabbage, radishes, and collards.
- nightshades—eggplants, potatoes, and peppers.
- umbellifers—dill, parsley, parsnips, and carrots.
- cucurbits—melons, boards, pumpkins, and zucchini (Sweetser, 2022).

You can also rotate crops based on their nutrient demands. Some plants are heavy feeders and some are not. You can alternate heavy feeders with light feeders to reduce the nutrient stress on the soil. Make sure that you maintain a written or pictorial record of these crop rotations.

Step 7: Create Your Teas and Inputs

It doesn't matter if you are farming the traditional way or following no-till practices, you can use compost teas and KNF inputs in your garden. These will increase your garden produce, reduce weeds, and control pests. Moreover, you'll be able to unlock higher levels of plant health. Compost teas and KNF inputs can be your best friends when the soil has been prepared, seeds have been sown, and you are still worried about the health and productivity of your plants; they can help you bring the best out of your soil.

If you are confused about your teas and input choices, I suggest that you start by brewing several compost teas and inputs and apply them to different areas of your farm/garden. Notice the results that each of these preparations produces and you can narrow down your options based on these results. You can continue to apply the preparations that are producing good results and leave the ones that don't work for you.

Step 8: Recheck the Soil

Try to perform the soil test at the beginning or at the end of each cropping season to check if anything has changed during that season. Although soil characteristics don't change that fast you never know, the preparations and composts that you apply throughout the season and the plants that you grow can alter soil pH, nutrient availability, and soil texture. Therefore, it's best if you recheck your soil periodically between different cropping seasons. This will allow you to adjust your strategy according to the soil's condition.

Step 9: Maintenance and Planning for the Future

You will have to restore your soil not just for the current season but several other years to come. The aim of soil restoration and regeneration is not just to enjoy a couple of good crop yields, it is to obtain rich soils that future generations can enjoy too. Therefore, it's important that you plan your agricultural activities towards regeneration and sustainability.

Sometimes poor soil quality is not your fault. Imagine moving to a new house where the soil is incredibly poor and you have no idea how the previous owners were treating their soil. You cannot just abandon that soil thinking that it has permanently lost its vitality. Soil can always be improved even when it seems completely destroyed. I am hopeful that if you follow these incredibly easy soil regeneration steps, you can restore the soil to its original form. This may take several seasons so you don’t have to hurry through these steps, but they will surely reap rewards that will continue for generations to come.

CONCLUSION

Soil is not just a medium for growing our crops; it is so much more than that. It is home to innumerable macroorganisms and microorganisms; it is the storage for important elements like carbon and oxygen; it recycles the nutrients between Earth and the atmosphere; and it is the reason we breathe and have sufficient food on our plates. Soil is the main factor implicated in maintaining environmental and food security for the human race all around the world. But we haven't been treating it very well. The entity that took millions of years to form has been severely damaged within the last 200 years. The decisions we made and the lifestyle we chose during those years have come to weigh heavily upon us as we have been focusing too much on crop yields and too little on soil health.

The world is on the brink of collapse solely because we have not been taking care of our soil. Currently, we are experiencing extreme climate events, global health issues, and food security challenges. Ecosystems and associated biodiversity are under threat. All because we have neglected our soil.

But there is still time. The damage is reversible and with little effort. We have to change the way we treat our soil. We have to shift our farming practices to less invasive, nature-based farming. First, a shift to no-till farming will help us reduce soil loss and preserve the native soil structure. Secondly, no-till farming techniques like crop rotation, cover crops, and mulching will help to enrich the soil with OM. That's the best possible way to restore your soil's fertility. Fertilizers will provide a temporary fix, but we cannot rely on them to produce food for an ever-increasing population unless we restore the soil's fertility back to the way it was. Using food scraps and organic waste, we can easily provide plants with OM while also reducing the greenhouse effect. Last, easy preparations like compost teas and KNF inputs can help us achieve new levels of plant health while maintaining sustainability and profitability in farming.

The government surely holds greater responsibility in changing the way the land is used and the food is grown, but your input matters too. Remember small steps matter! The way you farm now will determine the way our future generation lives. Even the smallest decision such as throwing a food scrap into a compost pile instead of the bin will create a huge difference in the future of the world.

To conclude, I want you to restore the soil and spread the message. The world needs more people to restore the soil than anything else, and you can play an active role in this process.

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SCAN ME

Ready To Take It A Step Further?

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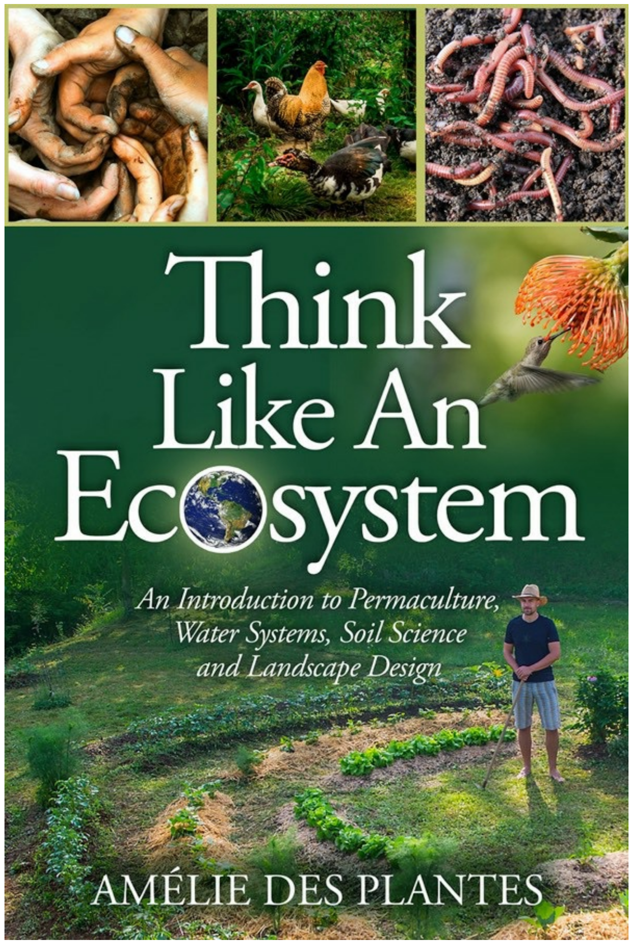

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