Appendix A. SOIL SYSTEMS

A.1 SOIL TEXTURE AND STRUCTURE

Soil physically supports the plant while permitting movement for the growing roots, as well as for air, water, and nutrients. The **texture** and **structure** of the soil both influence the amount and the size of the open spaces in the soil, and therefore influence a host of related factors of critical importance to the soil—principally:

a. the movement of air, water and nutrients to the roots

b. the development of an efficient root system it facilitates the by allowing roots and root-hairs to move easily throughout the soil; thus improving the plant's ability to find nutrients and water.

c. the removal and breakdown of certain toxins associated with intermediate stages of breakdown in organic matter (especially under anaerobic conditions).

A.1.1 Soil Texture

The ***TEXTURE*** is a rather formal definition that has been defined by soil scientists to facilitate the discussion of soils, and refers strictly speaking to ***the proportion of sand, silt and clay particles*** that comprise a particular soil sample.

Sand is soil particles with diameters from 0.05 to 2.0 mm

Silt is soil particles with diameters from 0.002 to 0.05 mm

Clay is soil particles with diameters < 0.002 mm

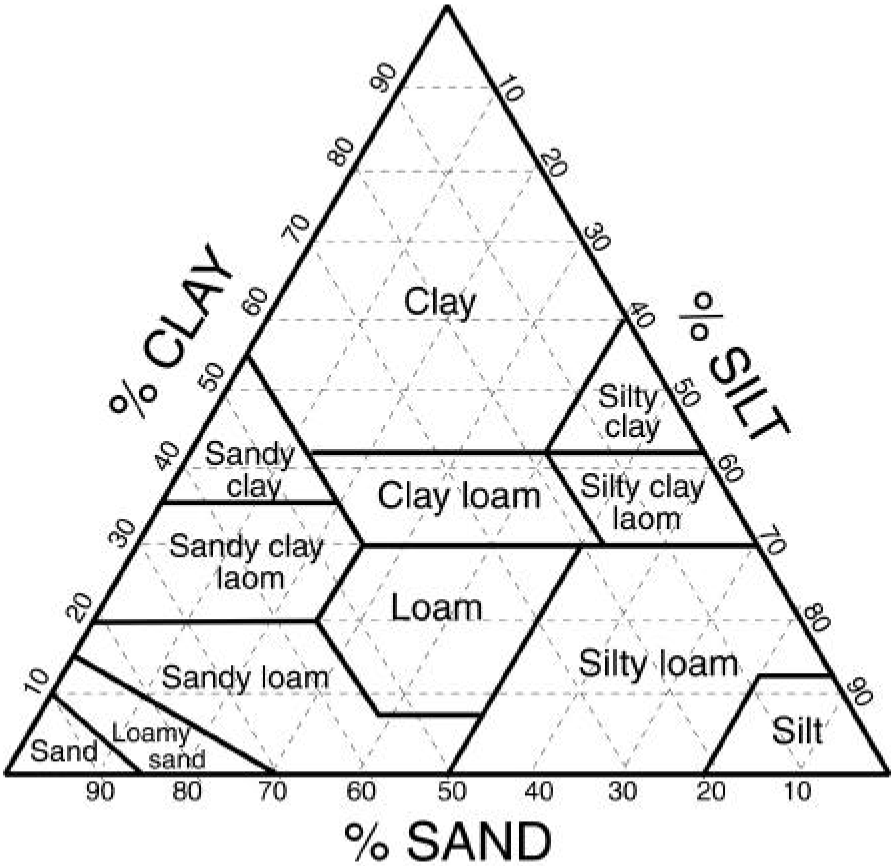
Soils may also be described as ***coarse*** or ***fine***; a coarse-textured soil has more sand, whereas a fine-textured soil has more clay. A soil whose properties are equally influenced by sand, silt, and clay is called a ***loam*** or loamy soil.

Soil texture is ***not*** something that can be changed in the short term. It is essentially what a particular farmer is "given" to work with. In the long-term, texture might be changed by events, such as flooding or landslides, in which large deposits of soil from another region are deposited in the soil. Note that the addition of organic matter does not, formally speaking, change the texture. It does, however, change the other characteristics of soil, such as structure, water-holding capacity, drainage, nutrient-holding capacity—in fact, almost every important characteristic except texture (this idea can be confusing for farmers and should be approached with care).

The texture of a soil is directly related to many important aspects of fertility: e.g., the ability of a soil to absorb and retain water, to hold plant nutrients, and directly affects the ability of roots to develop and move through the soil. Soils with a lot of clay are said to be "heavy" soils and tend to hold a lot of water, which tends to move slowly. Soils with a lot of sand are considered "light" soils, and tend to hold very little water, unless they also contain a lot of organic matter. Water infiltration (movement) in sandy soils tends to be very rapid.

The soil triangle

This type of graphic is uniquely used for situations where you have three elements in a system that combine to give 100%. In this case, soil texture is comprised of a combination of sand, silt and clay. This graph is probably not appropriate for farmer training, but should be interesting for trainers. The graph is sometimes confusing to read. Just remember that the 10% lines are always the longest, and the 90% lines are the shortest. After doing the soil texture "rolling" test you should be able to classify your soil into one of these categories.



A.1.2 Soil Structure

Soil ***STRUCTURE*** refers to ***the geometry or physical arrangement of the soil particles in relation to each other***. Unlike texture, soil structure can be modified by the farmer by activities such as tillage and water management. Other factors also affect soil structure, such as the action of insects, worms and microbes.

A poor soil structure may result in the need for greater amount of nutrients and a greater amount of water to bring about the same level of plant health, as a soil with good soil structure.

Soil compaction is the condition in which a desirable structure of a soil has been lost—specifically, pore spaces have been compressed. Compaction is a clear sign of a neglected soil. Compaction can be caused by many factors, and is often the result of several factors acting at the same time. Some of these factors include: loss of organic matter; use of granular soil insecticides (e.g., carbofuran) which kill worms and insects; and in mechanized agriculture is a frequent problem caused by the physical pressure of heavy equipment (tractors) moving over the soil surface.

A.2 The Soil Profile

Soil characteristics, such as texture and structure can be examined from small samples taken from the field, but it should be recognized that these are then being considered independently from the actual field conditions. In the field, the behavior of soil systems depends on characteristics of soils at several levels or depths. The analysis of a soil profile is an examination of the vertical distribution of soils. Classification of such systems is takes up much of typical soil science texts, and tends to be highly complex in nature.

In its simplest form, we can consider two layers of soil: a topsoil and a subsoil. The topsoil character can differ dramatically from what is found in the subsoil and therefore it is difficult to predict what a soil profile might be by simply examining the top soil.

A.3 Drainage

Fresh rainwater carries dissolved oxygen needed by the soil, as well as nutrients needed by the plant. So the soil must be ***porous*** enough to permit good drainage and to prevent the water from standing and becoming stale. If drainage is too rapid, however, the soil will lose both the plant nutrients (be subject to ***leaching***) and water. If the drainage is too slow, nutrients will be depleted in the areas surrounding the roots, and not be replenished at a rate adequate to the needs of the plant. Slow drainage also may cause ***toxicity problems*** related to ***anaerobic*** conditions (lack of oxygen), leading to build-up of intermediate breakdown products such as alcohols and acids that are toxic to the roots. ***Poor drainage (too fast or too slow) is a major cause of poor plant growth, but often one that farmers often don't appreciate sufficiently.***

Drainage at a particular location integrates several factors: clearly drainage is related to both the structure and texture of a soil. Furthermore, the drainage at a particular location will be related to the soil profile.

Ideal drainage may be achieved in a soil which contains open spaces of various sizes; wide spaces permit drainage, and small spaces trap water and allow for capillary movement of water.

Plants are continually growing roots into the soil to establish new sites of contact between root and soil. Most roots have a system of smaller and smaller branches, all the way down to microscopic "rootlets". However, ***the amount of root material in direct contact with the soil is still very small***. The plant, therefore, depends on the soil's ability to move enough water through the soil, in order to bathe the roots in water, food and oxygen.

The texture of a soil is not easy to change—the only way to do so would be to bring in a large measure of sand or clay, depending on what the soil lacked, and this would not be feasible except in a very small garden plot. The structure of the soil, however can be changed somewhat. One long-term goal of soil dryland soil management is to encourage the formation of **aggregates** of varying size. We often say that the soil has good "**tilth**" or a "**crumb**" or a "**granulated**" structure if it is well-aggregated.

Soil aggregates are particles of soil material—minerals and organic matter—bound together. Aggregation occurs in two phases: **formation** and **stabilization**. The aggregates are formed by alternating cycles of hot and cold, or wet and dry. These alternating cycles cause the particles to clump together (forming the aggregate), but unless the aggregates are "stabilized", they will quickly dissolve in the soil water. The clumps may be stabilized directly by the action of soil organisms (for example fungi, which physically surround the aggregate) or by cementing agents created from decaying organic matter, bacterial action, or even by soil passing through the gut of worms.

Plant roots also encourage soil aggregation. Roots pushing through the soil, together with dead roots, which cause cementing, help to form soil aggregates. Grasses and grains are particularly effective in promoting good soil structure, owing to the extensive network of their root system.

Soil organic matter (SOM) has a very significant positive effect on soil structure. SOM provides the raw materials for the cements which bind and stabilize soil aggregates, plus it stimulates the growth of micro-organisms and soil animals that contribute to aggregate stability. Residues high in carbohydrates are best in promoting stable aggregates. For example, straw is considered to be more effective than cow dung because it has more carbohydrates. Some people suggest that one of the most important benefits of SOM is the effect it has on soil structure.

Three practices are necessary to encourage a good soil structure:

- keep some kind of crop growing as much as possible throughout the year, to encourage maximum root growth;
- recycle crop residues to replace carbohydrates lost through biological activity; and
- minimize disturbance of the soil which would reduce biological diversity and accelerate the destruction of soil structure and organic matter.

A.4 Tillage

Tillage is the turning over of the top soil by mechanical action. It can sometimes improve soil structure by breaking up clods, and it can contribute to forming soil aggregates. This is most important for rainfed crops, but not for irrigated rice, in which soil structure is not as important.

In rainfed crops, tillage can also be damaging to the soil. For example, when the soil is too dry, tillage shatters or breaks up the soil aggregates. When the soil is too wet, tillage it compacts the soil. Tillage turns under and destroys the root structure of plants, leaving the most important top soil exposed to erosion by wind and water.

Moisture conditions during tillage are especially important with heavy clay soils. These soils should be moist when tilled but not sticky. One criterion for estimating the best time for working a clay soil is that it should be just dry enough that a person can walk into it without soil sticking to the shoes. Another is that a handful of soil squeezed into a ball should have no excess water running out and should crumble slightly when released.

Tillage tends to dry out a soil and must be timed carefully. Rewetting , especially after a long period of dryness, causes a flush of biological activity which rapidly uses up the organic matter. Rototillers tend to be very hard on non-flooded soils. They dry it out; they whip it up and shatter the aggregates; they destroy the capillarity; they compact the subsoil; and they destroy the earthworms and other soil animals.

A.5 What is soil pH?

The “pH” of a soil refers literally to the “Potential Hydrogen” and is a measure of the soil acidity. Technically, pH refers to the amount of hydrogen ion (H+) present in the soil water (or any kind of liquid), measured on a logarithmic mathematical scale. The technical description of pH is not important for our purposes. The important aspect of pH from a training perspective relates to how pH affects soil chemistry and plant nutrition, how to measure it, and how to manage it.

The pH is a scale of measuring acidity that goes from 0 to 14. A low pH (0-5) is acidic, and a high pH (9-14) is "basic" (lacking H+). The range of 6-8 is considered roughly "neutral" pH.

In many areas of the tropics we have acid soils (we have seen soil pH as low as 4.0 and heard of pH as low as 3.0). Soil acidity does not hurt the plants directly, but rather, it affects the ***availability*** of nutrients to the plant (this is also true for soils that are too basic).

We have also used a more general analogy: imagine the soil is like a "pantry" or some other local cabinet-like structure used in peoples homes to store food. In order to be able to "eat", the pantry needs to have food in it (a sandy soil or a soil under high rainfall conditions often has the nutrients leached away—the "pantry" is empty). Putting soil organic matter back into the soil is like "stocking the panty". A ideal soil with a good mixture of sand, silt, clay and organic matter is like a large pantry that is stocked with many kinds of food. If the soil pH is too low, or too high, however, this is like the pantry becoming increasingly smaller—there is no room for food, and if you try to add food to the pantry, the food must go somewhere else.

A.5.1 Improving Acid Soils

Lime is the most common material used to improve acid soils. Lime in pure form is calcium carbonate ($CaCO_3$). What is important in lime is not the calcium (Ca^{++}), although calcium is a required nutrient for plant growth. Rather, it is the carbonate (CO_3^{--}) that improves acid soils. It does this by combining with the hydrogen ion (H^+). Each carbonate molecule combines with two hydrogen ions, and in this way the lime "cleans up" the excess H^+ and raises the soil pH toward neutral.

The formal description of the reaction goes as follows:

$$2\ CaCO_3 + 3H^+ \Leftrightarrow 2Ca^{++} + HCO3- + H2CO3$$

for every two molecules of calcium carbonate, 3 ions of hydrogen are taken up (lowering the pH), producing 2 ions of calcium (which are now available for storage in the soil, or uptake by the plant), and one molecule each of bicarbonate and carbonate.

The amount of lime needed to raise soil pH to a neutral status depends on the type of soil and on the initial pH. Below is a rough guide to raising soil pH.

pH	Lime T/ha
4.0	10.24
4.1	9.76
4.2	9.28
4.3	8.82
4.4	8.34
4.5	7.87
4.6	7.39
4.7	6.91
4.8	6.45
4.9	5.98
5.0	5.49
5.1	5.02
5.2	4.54
5.3	4.08
5.4	3.60
5.5	3.12
5.6	2.65
5.7	2.17
5.8	1.69
5.9	1.23
6.0	0.75

A.6 THE CRITICAL ROLE OF SOIL ORGANIC MATTER

A.6.1 Soil Organic Matter

We have been looking at the distribution and flow of nutrients in ecosystems. We have learned that for Oxygen, Nitrogen and Carbon, the primary reservoirs are the atmosphere we breathe. We also learned that while oxygen and although Nitrogen must be processed by microorganisms living in plants and the soil before being accessible to the plants. For all other nutrients, the living plants and animals and the soil are the primary reservoir.

For all these nutrients, once they enter into living organisms, they tend to circulate, moving through the food web as organisms are eaten by other organisms. For example, nutrients initially taken up by plants might be eaten by an herbivore, which itself might be eaten by a predator, and so on. At each stage or “trophic level” (meaning “feeding level) energy and nutrients can be transferred in only a few ways: a certain fraction of the original plant or animal is passed on to the next trophic level, or returned to the soil—either directly, or in the form of waste products from digestion. In the case of energy, all organisms “respire” (breathe) and here energy in the form of heat and CO_2 is lost to the atmosphere. Unless the nutrients are physically removed from the system (such as happens with products after harvest), eventually, everything living dies and comes back to the soil. What happens then should be of interest to farmers because this soil organic matter (SOM), plays a critical role in the functioning of the ecosystem, and in the health of the soil and crops.

Soil OM is actually comprised of two parts: the living and the dead. The living parts include the “**microorganisms**”: the **bacteria**, **viruses**, **fungi**, plus a great many a host of larger animals like worms, termites, and beetles. Of greatest concern to us in this chapter, however, are the microorganisms (also called “microbes”), for these animals are responsible for the majority of the processing that takes place when a dead animal or plant enters the soil system.

“Feed the Soil and Let the Soil Feed the Plant”

A.6.2 Soil Microorganisms: “farmers’ friends”

The majority of soil-living organisms are bacteria and fungi and nematodes. While farmers may know that some of these organisms are the cause of disease for their crops, but actually, the vast majority of them serve a positive role. Many of the fungi serve to breakdown and process dead OM into smaller-and-smaller components. These organisms are called “**saprophytes**”. Many of the bacteria serve a useful function in transforming nutrients into forms that are then able to be absorbed by the plant roots. Still others—both fungi and bacteria--may act as predators and parasites to help protect the plant roots from attack by diseases and pests. In other words, just like in the above-ground system, there exist pests and natural enemies in the soil system as well!

A.6.3 Soil Organic Matter acts as a "Buffer"

Many farmers may thing that by adding inorganic fertilizers (NPK) to their soils they are "feeding their plants". In fact, as long as there is good soil organic matter in the soil, inorganic fertilizers do not go to the plant directly, rather 80-90% of the inorganic fertilizers are taken up into the life cycles of the Soil Microbes as these microbes grow and multiply. Only when the microbes die are the nutrients from their decomposing bodies broken back down into small molecules and freed into the soil to be taken up by the plant roots.

In exactly the same process, most of the nutrients from the breakdown of SOM itself will be taken up by growing populations of microbes. So we see that all nutrients, whether organic or inorganic, tend to be taken up by soil microbes first, before becoming available to the plant.

In this way SOM, together with the microbes that feed on it, will bind or capture nutrients in a form that allows the stable longer-term storage of nutrients, and their slow release into the soil and eventually into the roots of the plant. This is a much more efficient way to feed the plant because nutrients are released a little at a time over a longer period of time.

In contrast, soils with little or no SOM also have poor populations of microbes. As a direct result, the nutrients and microbes that process them are not available. Therefore, if farmers add inorganic fertilizers to their soils, the nutrients will float around in an "unbound" or free form. Some nutrients will be taken up directly by the plant roots, but the large majority will be lost to leaching by rainwater or irrigation water, or —in the case of N— volatilization and denitrification back into the atmosphere. In addition, the plant may be "flushed" with nutrients very quickly. Too much fertilizer, entering the plant too quickly, can cause problems with disease and with lodging (see section on "too much N").

A.6.4 Why does Soil Organic Matter promote microbe growth?

We have learned that plants take their carbon directly from the atmosphere, but are dependent on Nitrogen and other nutrients that are processed by microbes in the soil ecosystem. Microbes also need carbon for energy and Nitrogen for building proteins (although a certain group of them can "fix" nitrogen directly from the atmosphere). Unlike plants, however, microbes cannot get their carbon directly from the atmosphere. Instead, they are dependent on plant residues for their source of energy in the form of carbon compounds.

This is why returning plant residues to the soil is critical for maintaining the health of a soil and the productivity of a farming system: putting residues back into the soil feeds the soil microbes, which in turn, feed the plant

A.6.5 Carbon—Nitrogen Ratio

One of the most important characteristics of Organic Matter is the amount of carbon compared with the amount of nitrogen (or the ratio of Carbon to Nitrogen, written as C:N). As we have discussed, microbes have need for carbon for energy, and Nitrogen for growth and development. The bodies of bacteria have a certain ratio of C:N, usually about 8:1. However, different kinds of organic matter have different ratios of C:N. Almost always Organic Matter is much higher in Carbon than in Nitrogen. Rice straw, for example, has a C:N ratio of about 200:1. What occurs when a large amount of OM, with a high C:N ratio, is added to the soil is that microbes initially grow quickly in the presence of a new energy (carbon) source. However, as the Nitrogen in the OM is used up, the microbes draw upon the Nitrogen available in the surrounding soils. This brings them into a competitive relationship for any plants that might also be in the same soil. This can cause nitrogen deficiency in the developing crop if low-Nitrogen SOM is added to the soil just before planting the crop. Therefore farmers must be careful adding “unprocessed” plant residues.

This problem can be avoided in several ways:

incorporate the straw into the soil several weeks before planting the crop

add Nitrogen, in the form of urea, to the soil together with the straw

compost the straw first for several months before adding back into the field (compost has almost the perfect balance of C:N for soil microbes).

A.6.6 Anaerobic Decomposition and Poor Drainage

Because oxygen movement is 10,000 times slower in water than in air, the oxygen supply from the air cannot meet the oxygen demand of "**AEROBIC**" (or oxygen-breathing) organisms in the soil; hence, the development of "**ANAEROBIC**" (or lacking oxygen) conditions in about 2 hours after the flooding of a field.

Flooding a field causes the death of many organisms, and therefore the release of nutrients locked up in their bodies.

In an anaerobic environment, ammonia and ammonium (NH3 and NH4+) are stable products of nitrogen metabolism in bacteria, however nitrate (NO3) is rapidly denitrified and lost back into the atmosphere as N2 gas.

Low yields in China have been attributed to poor drainage. For heavy clayey paddy soils, which are derived chiefly from alluvial and lacustrine deposits (like the Jalur Pantura in northwestern Java), poor yields are attributed to generally small pore spaces, which are poor in aeration and permeability, although good in water retention ability.

To improve soils with poor drainage, to promote their fertility, and ultimately increase rice yields, it is essential to provide proper drainage, thereby improving aeration in the root layer. Drainage is not only effective in improving soil characteristics, but also a practical technique for substantially increasing rice yields—as proven by many experiments in China and elsewhere.

Drainage conditions also inevitably affect the decomposition and accumulation of organic matter. There is always a greater accumulation of organic matter in poorly drained paddy soils simply because it does not break down as rapidly (fewer microbes). Under good water regime, soil OM plays an active part in the improvement of physical properties of paddy soil. On the other hand, with a poor water regime (poor drainage), it is difficult to improve soil physical properties and increase soil fertility by raising the content of soil OM.

Appendix B: Principal Nutrients

B.1 Nitrogen

N is the symbol for the atom **NITROGEN**. N is an essential nutrient for all living plants and animals, and in a manner of speaking N represents the "action" of life. N controls the movement of energy and materials and the growth of the plant by its large contribution to every complex protein (e.g., chlorophyll, enzymes, hormones).

The major reservoir for nitrogen is in the atmosphere. Roughly 80% of the air we breathe is nitrogen gas (two atoms of N, or N_2), but neither animals nor plants directly take up N_2 from the air. The reservoir of nitrogen is only very slowly cycled into the soils and water via the action of microorganisms that **FIX** the nitrogen from the atmosphere into the bodies of the microorganisms themselves. These microorganisms live mostly in the soil, but some live inside plants. When nitrogen is fixed, it is taken into the bodies of certain types of bacteria, and used directly by them to help grow more bacteria. When these bacteria then die (bacteria do not live a very long time), the nitrogen, in the form of **PROTEINS** and **ORGANIC MOLECULES** and along with other nutrients in their bodies are then broken down by the action of other **SAPROPHYTIC** (decomposer) bacteria and fungi, which use these nutrients in their own growth, but also release part of the nitrogen into the soil in forms that can be taken up by plant roots and by other microbes. The process of decay of dead organic matter, thereby releasing nutrients to the surrounding soil is called "***mineralization***". The process of nutrients again being taken up and incorporated into the bodies of living microbes is termed "***immobilization***".

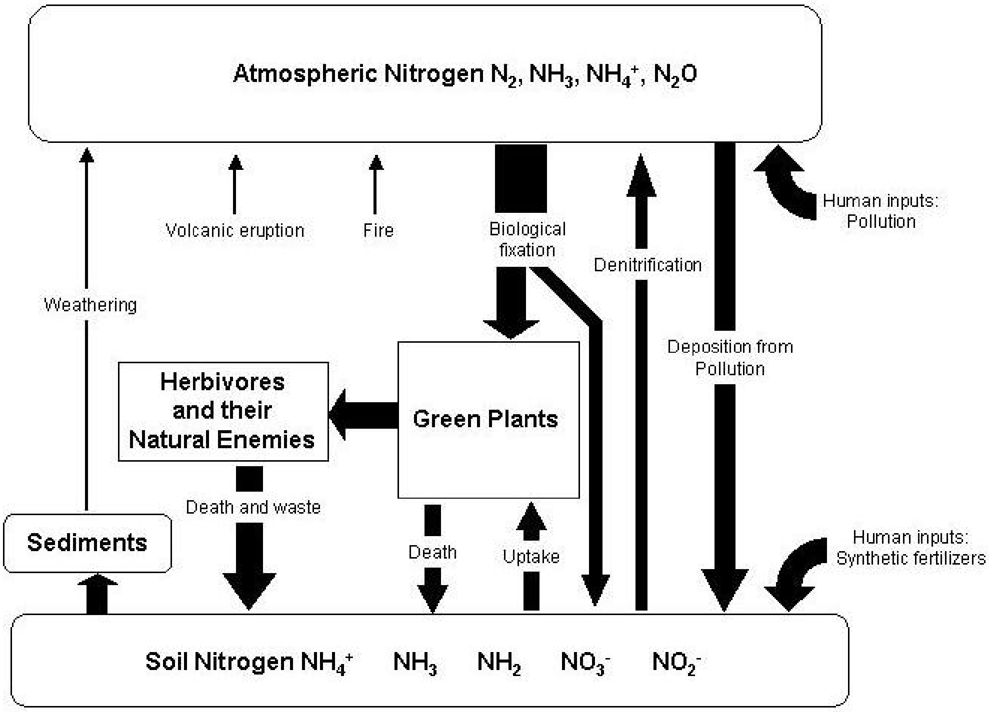
The principal pathway for N_2 to enter living organisms from the air is via certain types of bacteria. Many of these bacteria live in soils. Others, like **Cyanobacteria**, live in aquatic systems like rice paddies, inside the cells of specific kinds of algae (blue-green algae). Cyanobacteria in a rice paddy may fix up to 100-150 kg N/ha/year. Other bacteria, such as those of the genus **Rhizobium**, live inside the roots of leguminous plants, and still others live inside the leaf cells of plants, like *Sesbania*. The reason Cyanobacteria and Rhizobia are so successful at fixing large amounts of nitrogen is because each has access to large sources of energy. The Cyanobacteria are associated (live inside of) algae. Through photosynthesis the algae is able to offer the bacteria carbohydrates (C), and in return, the bacteria fix nitrogen, some of which benefits the plant. In a similar manner the Rhizobium bacteria are associated with the roots of plants, receive food (carbon) from the plant roots, and "pays back" its host with nitrogen.

As a result of the limited paths whereby N finds its way into living systems, of all the soil nutrients, N is the most likely to be lacking in the soil. Yet all life requires N in large amounts; as a result, natural supplies of N are almost always limited, and most plants are very good at competing for N.

The nitrogen cycle

It is one of the mysteries of life that although nitrogen is needed by all living things in fairly large amounts, and although our atmosphere is a huge reservoir of nitrogen, the paths by which nitrogen can enter ecosystems are very limited—the doorway opens through a few species of bacteria. As a result, nitrogen tends to be a **limiting nutrient** in the growth and development of many organisms, most especially plants. A limiting nutrient is the one (and by definition, there is only one at a time) nutrient that is in greatest demand and whose absence slows the entire process of growth.

Nitrogen can take several forms in the soil, depending on how it combines with other atoms. In addition to the many forms in which nitrogen is found in living things, nitrogen can be found in inorganic forms in the form of nitrogen salts: ammonium [NH_4^+], nitrite [NO_2^-], and nitrate [NO_3^-]. Like any salt, all three forms of Nitrogen salts are highly water soluble and as a result can be found most anywhere on the surface of our planet. The Nitrogen salts are very actively cycled and recycled back and forth between inorganic forms and organic forms. The two main forms accessible to uptake by plant roots, and therefore the forms we will focus on, are NH_4^+, and NO_3^-.



Synthetic nitrogen is applied at a rate of about 40 million tons per year, world-wide. Deposition (entry into the soils) of nitrogen from pollution is roughly 100 million tons per year. This is mostly in the form of nitrous oxide (N_2O, one of the “greenhouse gases”) and ammonium (NH_4^+) in “dry deposition”, and in the form of nitrate (NO_3^-) and ammonia (NH_3) in wet deposition (rainfall). Nitrogen input to soils from pollution can be as much as 40 kg/ha per year. Biofixation of N accounts for roughly 140 million tons per year world-wide.

Too little nitrogen

If nitrogen in the soil is low, almost all plant functions are disturbed and the most direct result is that plant growth is stunted and pale green to yellow. Four nitrogen atoms surround a single magnesium atom to form the core of the chlorophyll molecule; hence, limited nitrogen reduces the photosynthetic capacity of the plant. Nitrogen is highly mobile in plants, so when nitrogen is low it drifts from older leaves to newer leaves and the older leaves will turn light green, yellow or even pink. This is one good indicator of nitrogen deficiency, although you have to be careful not to get this confused with one of several diseases or even soil drainage problems.

Too much nitrogen

Too much nitrogen can be poisonous to a plant. If too much nitrogen is present, the plant diverts energy, carbohydrates, water and minerals in an attempt to digest and get rid of the excess nitrogen. As a result, a plant's health is thrown out of balance by too much nitrogen. Too much nitrogen causes:

- ⇨ plants to become overly succulent,
- ⇨ tubers to become watery and rot,
- ⇨ rice plants to become too tall and weak and "lodge" (fall over),
- ⇨ flowering and fruiting may be delayed,
- ⇨ fruits to ripen unevenly,
- ⇨ fruit vitamin A and C content to drop,
- ⇨ increased problems with disease and insect pests (for example, sheath Blight and many kinds of sucking insects do better on plants having very high levels of N)
- ⇨ leafy vegetables like lettuce to build-up toxic nitrates in the leaves (nitrates and nitrites have been shown to cause cancer in animals, and exports of leafy vegetables from some countries have been cancelled after laboratory analysis shows nitrates to be above a certain safe limit.

Inorganic" nitrogen: urea

Urea is considered an "inorganic" or "artificial" form of Nitrogen. In fact, the origins of urea are from natural, organic substances. Urea derives from **NATURAL GAS,** which is taken out of the ground in much the same way that people drill for oil. The fact that natural gas takes millions of years to be created means that once we use up the natural gas we find in the soil, we will not be able to find more. For this reason we call natural gas (and therefore urea) a **"non-renewable"** resource. Urea was created from organic substances that millions of years ago were trapped in soil sediments under anaerobic conditions and therefore never had a chance to be decomposed completely. Urea is made up of two molecules of (NH_2) tied together with a carbon and oxygen atoms (CO), so the molecule is written as CO[NH2]2 When urea is added to soil it is broken down by water into two molecules of ammonia (NH_3), and CO_2 is released in the process. For urea to be decomposed into ammonia requires the action of microorganisms.

Several studies have been done through the years using "labeled" nitrogen, that is, nitrogen with a special mark on the atom, so researchers can follow exactly where specific nitrogen atoms goes. These studies show that when urea is applied to the soil in a rice field, ***under the best of conditions***:

- ⇨ 20% ends up in the grain,
- ⇨ 12% ends up in the straw,
- ⇨ 3% in the roots,
- ⇨ 23% is left in the upper 30 cm of the soil, and

the remaining 40% is lost through denitrification and through leaching.

Nitrogen loss from the soil

"Volatilization" of ammonia can take place in the soil when it simply evaporates into the air and is just carried away. This happens after heavy applications of manure, and it can occur when urea or ammonia fertilizer is used if the soil pH is high. Recent research, however, has shown that losses can be reduced by adding calcium or potassium salts to the soil.

"Leaching" is the washing out of a nutrient from a soil whenever excess water percolates through the soil, carrying with it any dissolved nitrogen. The best ways to minimize nitrate leaching are to promote biological activity with carbon-rich residues and to maintain a good plant cover, like a green manure. The leaching of dissolved organic materials carries away not only nitrogen but also phosphorus, sulfur and trace elements. To minimize leaching, the soil pH should be maintained near neutral. This maximizes biological activity, which aids in the stabilization of soluble organic substances. Also the calcium in the lime is a good binding agent and reduces the instability and solubility of organic residues.

Farmers remove nitrogen from the field every time they harvest the crop. A large proportion of the nitrogen in animals and plants is used in the making of proteins. Therefore, in most plants this means that the majority of the nitrogen ends up in the seeds. As a result, when a rice plant is harvested, 70% of the nitrogen in the entire plant is taken away in the form of the harvested grain, leaving only 30% remaining in the roots and straw.

"Denitrification" is often the most important cause of loss of nitrogen. Denitrification is the return of nitrogen to the atmosphere takes place when three conditions are satisfied: 1) nitrates (NO_3^-) must be present, 2) organic matter must be present (in order to support the bacteria that transform or "denitrify" nitrates back into N_2 gas, and 3) conditions (at least in pockets) must be anaerobic (low oxygen).

Too much organic matter can encourage denitrification, because an excess produces enough biological activity to use up all the available oxygen. The amount of OM residues that can cause denitrification depends on the texture of the soil and the coarseness of the organic residues. An open sandy soil can absorb more compacted organic residues than a clayey soil.

Usually, ***the more one tries to force nitrogen into the soil, the greater the losses of nitrogen from the system***. If a soil is overfertilized with nitrogen, it may find a way to get rid of the nitrogen almost as fast as the farmer puts it on. If the nitrogen is spread in ammonium form, the soil may either cause it to be volatilized or to be rapidly nitrified (converted to nitrate form) and soon afterward lost as a gas by denitrification. If the nitrogen is initially in nitrate form, it may be denitrified, or it may be leached into the groundwater. The leaching of synthetic fertilizers into lakes, rivers and oceans has had a major negative impact due to the stimulation of "algal blooms", whose subsequent death and decay by microbes robs the water body of oxygen, often causing massive fish kills.

These facts, coupled with the fact that nitrogen fertilizers are often a significant cost to farmers, are very good reasons why farmers need to learn how to better manage their nitrogen inputs.

B.2 PHOSPHORUS (P)

Short-term storage of energy: ADP & ATP

Phosphorus (P) is one of the major nutrients that farmers apply when they buy inorganic fertilizers. P has several important roles, notably it is important in the construction of the genetic material, DNA (hence, is found in important concentrations in seeds). Also, P is associated with the short-term storage of energy captured from the sun.

ADP & ATP: the "rechargeable batteries" in the plant

One role of P is to act as the energy transfer agent. It works as such by being attached (or unattached) to a small, but very important molecule. The ADP (Adenosine di-Phosphate) molecule has two phosphates attached (di = two). The ATP (Adenosine Tri-Phosphate) molecule has three phosphates attached. Attaching the third phosphate atom to ADP to make ATP requires (and thereby stores) energy. Similarly, when the ATP molecule has a P "broken off", it gives up energy that can be used by the plant. In other words, ADP is like a battery with the charge gone out, and ATP is like a charged battery.

The energy-charged ATP molecule can and does go everywhere inside the plant, from the smallest root to the tip of the flower, to the inside of the grains. The ATP molecule is used by every cell in the plant to give up energy in order that the cell can do its work. In fact, ATP is found, not only in every plant, but in every animal on earth! It is the "common currency" of energy transfer for all life on earth, from the smallest bacteria to the largest whale or the tallest tree.

Behavior in the soil

The amount of P found in surface soils ranges from about 200 kg/ha in sandy soils, to about 2,000 kg/ha in soils derived from rocky subsoils. Chemical weathering results in ***solubilization*** of orthophosphate ($H_2PO_4^-$) and pH < 7.2 and HPO_4^{2-} at ph > 7.2. This is the form in which phosphate is available to the plant, and usually accounts for not much more than 1% of the total phosphorus in the soil in any location. This is because the release of orthophosphate (either through solubilization or by application of phosphate fertilizers) is followed by ***precipitation*** (the forming of insoluble solids from chemicals in solution). Phosphorus goes out of solution in the form of iron and aluminum phosphates in acid soils, and calcium phosphates in basic soils. These reactions result in low orthophosphate concentrations at pH levels above or below about pH 6.5.

Another source of phosphorus is from organic matter. Total organic phosphorus accounts for usually between 30—50% of total soil phosphorus, and the ***microbial pool*** (total amount of living and dead microbes) represents the majority of the actively cycling pool of phosphorus.

Not enough P

Seeds contain a large amount of P, so a deficiency in P might be indicated by plants with small seeds. P also stimulates root growth. This can be shown by putting a small source of P in the soil near the plant roots and then digging down to observe the roots in the area of the P. They should be longer, stronger and with many fine root hairs.

P is not taken up by the roots as well as is N, so P can be overwhelmed by too much N. P is very rapidly bound by several factors in the soil, so any free P taken up by the plant must come from very close by the roots. One problem with P is that it is not very "soluble" (able to be broken into small molecules and to move through the soil and water). In a soil which has a good amount of oxygen ("aerobic" conditions) P is more soluble. One benefit from the solubility problem is that it takes a very long time to leach P from the soil. Hence, ***farmers that add P every season may have built up much more than they need***.

Factors affecting P movement

The pH of a soil affects mobility (movement). If the soil is near neutral (pH 6.5-6.8) then P optimally available to plant roots. Highly acidic or basic soils have almost no P available to the plant, except that which is released from decaying organic matter. Organic matter and associated microorganisms have a strong influence on P availability. P released from decaying organisms is readily available for uptake by plants. For example, P is picked up by fungi and spread throughout the mycelia, and therefore spread throughout the soil. When the fungi dies, this P is immediately available to plant roots. Furthermore, many soil microorganisms release acids which are good at dissolving inorganic P. Finally, mycorrhizae (a type of fungus associated with almost every plant) invades plant roots to extract carbohydrates. In return, the fungus passes on minerals, including P, to the roots. ***Fungi helping roots with P extraction is analogous to bacteria helping roots by fixing N***.

Maintaining enough P in your soils

The best ways to ensure enough P is available is: 1) keep the pH near neutral, 2) assure sufficient water, and 3) promote high populations of microorganisms by maintaining a good regime of organic matter returning to the soil.

B.3 POTASSIUM (K)

Potassium (K) is the third major nutrient often added to soils by farmers. Unlike the other nutrients, K is not found inside plant cells, but exists in the fluids that move through the plant. K affects the "osmotic pressure" of the plant, by keeping the plant fluids balanced in terms of salts and water movement. When K is deficient, water fills the cells and they become soft and the plant loses strength. Plants deficient in K tend to be more susceptible to drought, insects and disease.

Potassium is involved in photosynthesis, in the creation of starch in roots, and in the creation of proteins. K is especially critical for root crops.

Plants are better able to uptake K compared with Phosphorus (P) or Magnesium (Mg). In fact, ***a plant will absorb as much K as there is available, even if it doesn't need it***. As a result, too much K causes deficiencies in the other nutrients because the plant is too busy taking up K to take up the others, even though it may need the others more!

Two mechanisms account for the fact that K is not rapidly leached from soils:
1) it is very small and gets trapped in cracks in clay particles (but also isn't much available to roots as a result), and
2) K is attracted to the surface of clay particles and organic materials (see exercise on the structure and function of clay particles).

With a steady program of recycling organic matter, potassium will not be a problem. As an example, almost 98% of the potassium in a rice plant is found in the straw. Therefore, as a general rule, if the carbon-to-nitrogen ration (C:N) is high, so too will be the potassium-to-nitrogen ratio (K:N).

Nutrient	Crop Plant	Deficiency Symptom
NITROGEN	General	Nitrogen deficiencies are most common on soils highly depleted of organic matter, but N is often the most limiting crop nutrient and symptoms can occur in any soil where yearly inputs of N are low.
	Legumes	Since most legumes can supply their own N needs through symbiotic fixation, deficiencies generally do not occur unless the rhizobial symbiosis is not functioning effectively. N-deficient legumes have pale green or yellow leaves, starting with the lower leaves.
	Maize, Sorghum, and Small Grains	Young plants are stunted and spindly with yellowish-green leaves. In older plants, the tips of the lower leaves first show yellowing up the mid-rib in a "V" pattern, or there may be a general yellowing of the entire leaf. In severe deficiencies, lower leaves turn brown and die from the tips onward.
	Vegetables	Tomatoes first show stunted growth and loss of normal green color in the younger, upper leaves; the whole plant gradually becomes light green to pale yellow; veins begin to develop purple color. Flower buds drop and fruits are undersized. Cucumbers and squash first show leaf stunting and a loss of deep green; stems are spindly and fruits are light in color. Other vegetables show a general leaf yellowing.
PHOSPHORUS	General	Phosphorus is most available at pH or around 6.5. Crops growing on very acid or very alkaline soils often show deficiencies. In many acid tropical soils, P is the limiting factor in crop growth.
	Legumes	Phosphorus deficiency symptoms are not well defined in legumes. Stunted grown, spindly plants and dark green leaves are the main symptoms.
	Maize, Sorghum, and Small Grains	Deficiencies are most likely during early growth; stunting is common, without clear leaf signs. Severe deficiencies cause a purplishcolor in corn and sorghum, starting at the tips of the lower leaves (disregard purple stems). Small grains show a bronze coloration instead of purple. Ears from P-deficient maize plants are somewhat twisted, have irregular seed rows, and seedless tips.
	Vegetables	Leaves of most vegetables first fade to a lighter color. Tomato and cabage family plants develop a purple color on the undersides of the leaves or along the veins.
POTASSIUM	General	
	Legumes	In broad leaved legumes like soybeans and field beans, early signs are irregular yellow mottling around the leaflet edges, especially in the lower part of the plant. This turns into a brown, dried margin that may move in to cover half the leaf.
	Maize, Sorghum, and Small Grains	In miaze and sorghum, symptoms are rare the first several weeks of growth. Later, the margins of the lower leaves turn yellow and die, starting from the tip. Potassium-deficient plants have short internodes and weak stalks. Ears from K-deficient maize are often small and may have pointed, poorly seeded tips. It is difficult to dagnose K deficiency in small grains.
	Vegetables	Tomatoes will grow slowly and have a dark blue-green color; theyoung leaves become crinkled; older leaves turn dark blue-green and then develop a yellow-green color around the margins. Fruits may show a blotchy ripening pattern. Cabbage plants first show bronzing at the leaf edges which turn down and dry out.
MAGNESIUM	General	Magnesium deficiencies are most common on acid, sandy soils, or soils that have been limed with a material lacking magnesium.
	Legumes	In early stages soybean leaves become pale green between themain veins and then turn a deep yellow, except at the bases.
	Maize, Sorghum, and Small Grains	In maize and sorghum, a general yellowing of thelower leaves is the first sign; eventually, thearea between the veins turns light yellow to almost white, while the veins stay fairly green. As the deficiency progresses, the leaves turn reddish-purple along their edges and tips starting at the lower leaves and working upward. Symptoms are not clear-cut in small grains.
	Vegetables	Cabbage, cucumber, watermelon, tomato, eggplant, and pepper are the most susceptible. Tomatoes get brittle leaves, which may curl upwards; the veings stay dark green while the areas between turn yellow and then finally brown.