What is a nutrient?

The link between soil elements and plant nutrients.

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Farmer, gardeners, horticulturalists, crop consultants, soils scientists and agronomists have differing ideas regarding nutrients. Perhaps that's because the term soil fertility is often conflated with plant nutrition since they are closely related concepts. In this paper we'll define nutrients in terms of the origins and relationship of *elements* to each other, focusing on the nutrients that should be present in soil to grow healthy plants. This paper also gives a short summary of the role of the anion nutrients in the life of a plant. Later papers will cover how these nutrients cycle in the soil and how they are added to soils as fertilizers at various points in the cycle. The reader can also find out more about individual nutrients in plant physiology in a course that focuses on crops and plants.

Plants, animals, microbes and other life forms need external sources of ***elements*** in order to grow and reproduce. Elements are "irreducible" constituents, that is, they are materials that cannot be further simplified. The earth is made up of about 90 naturally occurring elements. Elements are shown Table 1. The table is arranged in repetitions or a "periodic" way to show how many protons or neutrons are in the nucleus of each element. (That number of protons coincides with each element's "periodic" number). As most readers probably recall from high school chemistry, each letter(s) in the box is a shorthand name for an element. For example Oxygen is element #8 and is abbreviated as "O". Oxygen and silicon (Si) (element #14) are the most abundant elements on earth, next are aluminum (Al) (#13) and iron (Fe) (#26). Iron is abbreviated "Fe" because the Latin word for it is "Ferrous".

Some elements are nutrients, while others are not. For example, all plants require iron, but none require aluminum; and very few require silicon. Sodium, which is very abundant in nature, is not required by plants, and though some plants can use it, it is toxic in high concentrations. Animals, on the other hand, do require sodium. To recap – not all elements are nutrients, but all nutrients are composted of elements.

Minerals are generally defined as naturally occurring, homogenous, and inorganic. In this sense, inorganic simply means "does not contain carbon". Each mineral has a well-defined color, hardness, crystalline structure and chemical composition. Some minerals are composed of a single element, as is the case with both gold and silver.

It gets confusing when organic farmers also refer to some things they use, like kelp, as "a mineral". Kelp is a sea "weed" (actually now it is classified as an animal but that's another story) that is dried down to flakes – it contains trace minerals like iodine, but kelp is not itself a mineral.

The amounts of nutrients naturally occurring in a given soil depends on the parent rock material of the soil as well as the climate that has weathered the rock. **Soil fertility** is defined by Foth (1) as "the quality that enables a soil to provide the proper compounds, in proper amounts, and in the proper balance, for growth of specified plants when temperature and other factors are favorable."

Table 1. The sustainable agriculturalist's period table of elements important in plant nutrition

+1 +2 cations

Stable. Anions. Reactive. Stable

+1	+2											+3	0	-1	-2	-3	
H^{1}																	He^{2}
Li^{3}	Be^{4}											B^{5}	C^{6}	N^{7}	O^{8}	Fe^{9}	Ne^{10}
Na^{11}	Mg^{12}											Al^{13}	Si^{14}	P^{15}	S^{16}	Cl^{17}	Ar^{18}
K^{19}	Ca^{20}	Sc	Ti	V	Cr	Mn^{25}	Fe^{26}	Co	Ni	Cu^{29}	Zn^{30}	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo^{42}	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh	Uns	Uno	Une	Unn								

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr^{103}

(The period table has more than 115 elements, many with higher period numbers are not found in nature)

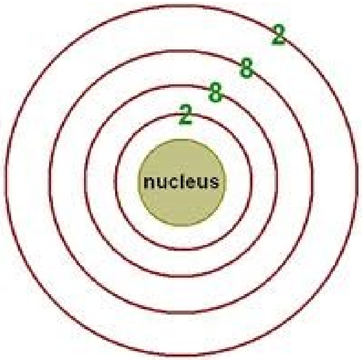
Why are we talking about the periodic table of elements in a soils course? It's because we go back to this table to find the foundation of chemical attractions, soil fertility and plant nutrition. We need to get re-acquainted with the elements just a bit. Many of us have seen the periodic element table, but not in the context of agriculture. It's really rewarding to understand the outcome - fertilizers and how to use them in organic agriculture - when one first sees the whole picture of how the elements relate to each other in the table as well as the elements' role in the plant.

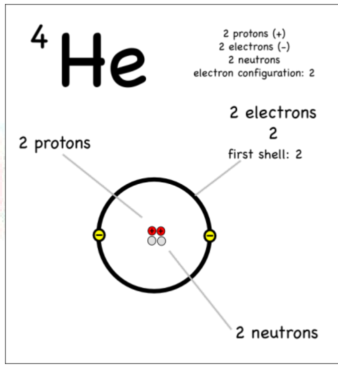
Let's start by looking at a few "agricultural" elements and their period numbers and how this ends up giving them a slightly positive or negative charge. Remember that electrons have a negative charge, they are symbolized as e-. Protons have a slight positive charge, they are hungry to mate with an e-.

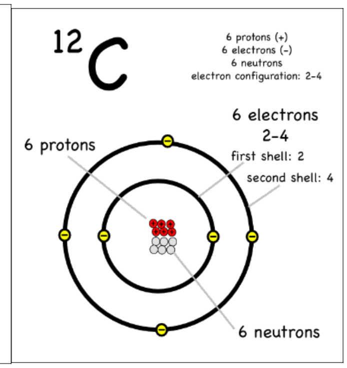
element	symbol	Periodic number	protons	electrons	Charge	outcome	Ionic form of the element
hydrogen	H	1	1	0	+1		H+
helium	He	2	2	2	0	stable	
carbon	C	6	6	6	0	Stable	
oxygen	O	8	8	8	0	stable	
nitrogen	N	7	7	7	-1	anion	varies
sodium	Na	11	11	11	+1	cation	Na+
magnesium	Mg	12	12	12	+2	cation	Mg+2
phosphorus	P	15	15	15	-1	anion	varies
sulfur	S	16	16	16	-2	anion	varies
potassium	K	19	19	19	+1	cation	K+
calcium	Ca	20	20	20	+2	cation	Ca+2

The elements are always in some ionic form or compound when they are in soil solution and are ready to be taken up by plant roots. You've previously read about cations (cat-eye-ons) and Table 2 really shows what an anion is. Anions can be thought of as elements with a slight negative charge. Anions carry one or more extra electrons. Elemental N and P both carry one more electron in their outer most atomic ring than they have protons to balance with in their nucleus. Sulfur has two extra electrons and thus an ionic charge of -2.

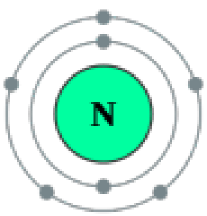
The following representations of the elements show the same information as in Table 2. Recall that the innermost ring contains just two electrons. The first circle below shows a basic atom and the number of electrons in each orbital ring that would make it stable When the electrons and protons are equal, the element is very stable and unreactive, like helium (He) and carbon (C).

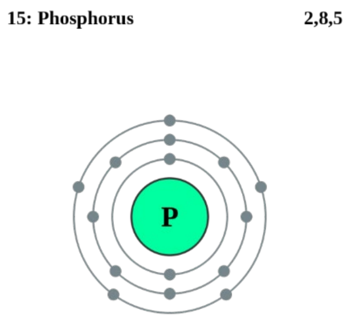


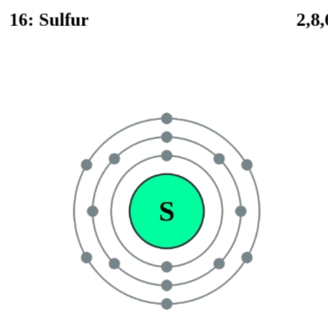




The anions Nitrogen, Phosphorus and sulfur are shown below.



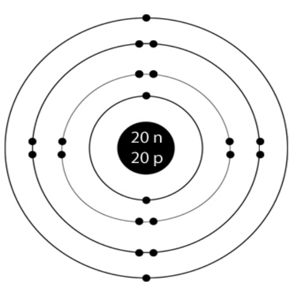


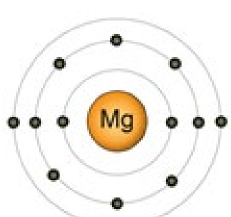


The debate over soil balancing and the ratios of Ca^{+2} and Mg^{+2} for example, can be better understood by noting the relationship between the two elements as shown in the period table. Calcium is a “bigger” element than magnesium, that’s how it is thought to “open” the soil when it inserts itself into a layer of clay. Organic farmers use knowledge like this as a substitute for synthetic, chemical shortcuts to soil, plant, and animal health.

Calcium +2; only 18 e- but 20 protons

Magnesium +2; only 10 e- compared to 12 protons





Note the Magnesium molecule is smaller because it has one less ring of electrons. ***.*** *Both of these cation molecules have two electrons hanging out in the outer ring* ***.***

What nutrients are in the plant's body?

Carbon, hydrogen, oxygen. Although hydrogen (H) and oxygen (O) and carbon (C) are elements, they are generally not called "nutrients" because they are usually abundant in water and air. Remember also that the plant body is made up mostly of carbon, hydrogen and oxygen. These elements are synthesized, or knitted together using energy from the sun to form carbohydrate compounds, often referenced as CH_20. Recall that this is the plant process we call photo (sun) synthesis (knitted).

Table 2 below summarizes the 13-15 elements essential plant for plant growth that are considered nutrients. The table lists the elements in order according to an average concentration in plant tissues. The table below also shows the amount of the element found in a typical soil. It also gives a brief description of the nutrient's role in the plant.

Table 2. Elements required by plants listed in order of how much of it (%) is in a typical plant's body.

	Macro-nutrients	It's available form in the soil [A]	% in typical soil	% in typical plant (%DM)[B]	Where is it found in the plant? What role does it play?
1 N	nitrogen	NO_3^- or NH_4^+	0.1	1-3%	Amino acids, proteins, DNA, chlorophyll, enzymes
2 K	potassium	K^+	1.5	0.3 - 6%	Enzymes, amino acids. Makes proteins. Activates enzymes, opens/closes stomata
3 Ca	calcium	Ca^{+2}	0.5	0.1-3.5%	Cell walls, enzyme cofactor, cell permeability
4 P	phosphorus	H_2PO_4 or HPO_4^{-2}	0.06	0.05-1.0%	Energy compounds i.e. ATP, co-enzymes, Nucleic Acids i.e. DNA. Phospholipids
5 S	sulfur	SO_4^{-2}	0.05	0.05-1.5%	Part of some amino acids and proteins and the very important Co-enzyme A molecule
6 Mg	magnesium	Mg^{+2}	0.4	0.05 - .07%	A part of the chlorophyll molecule. Activates many enzymes.
	Micro-nutrients			Parts per million (ppm)	
7 Fe	Iron	Fe^{+2} or Fe^{+3}	3.5	10-1500	Synthesis of chlorophyll, cytochromes and ferredoxin
8 Mn	Manganese	Mn^{+2}	0.05	5-1500	Activates some enzymes
9 B	Boron	BO^{-3} or $B_4O_7^{-2}$	0.002	2-75	Influences Ca^{+2} utilization, other unknown functions
10 Zn	Zinc	Zn^{+2}	0.001	3-150	Activates some enzymes
11 Cu	copper	Cu^{+2}	0.0005	2-75	Activates some enzymes
12 Mo	molybdenum	MoO_4^{-2}	0.0001	0.1-5.0	Nitrogen metabolism
13 Cl	Chlorine	Cl^-	-	100-10,000	Cell osmosis, O_2 production in photosynthesis
	Essential in some plants				
14 Co	Cobalt	Co^{+2}	-	trace	Required by nitrogen fixing microbes associated with legumes
15 Na	Sodium	Na^{+2}		trace	Osmotic balance in some desert plants and C_4 plants
	Cations have (+) charges		Anions have (–) charges		

Available form. Nitrogen, phosphorus and sulfur are anions and the form in which the plant takes them up from the soil has always been thought to be conjunction with oxygen, as shown in the 3rd column. Cationic nutrient elements exist in the soil solution in ionic forms and are taken up by the plant as cations.

Macro-nutrients. Nitrogen, phosphorus potassium, are *primary* macro-nutrients while calcium magnesium, and sulfur are sometimes referred to a *secondary* macronutrients. A macro-nutrient is needed in relatively large amounts by the plant as measured in "percent of dry matter" of the plant's body. In other words, if you took 100 grams of the plant and dried it, got rid of all the water, the ashy material that is left may contain about 2.5 grams (g) nitrogen, 2g potassium, 2 g calcium, 0.7g phosphorus, 0.06g sulfur and 0.06g magnesium – depending on the plant.

Micro-nutrients are measured in parts per million rather than a percent of dry matter. This tells us that micronutrients, while essential to plant metabolism are needed only in very tiny amounts. The micro-nutrients are not "body building" components, but rather they are keys or tiny locks in enzymes that allow the plant to function.

For an analogy, envision a car. The bulk of the car is compose of metal in the frame and the body – that is like the CH_2O carbohydrates in a plant body. The primary macronutrients might be rubber, glass, fiberglass/plastic – much like our N, P and K. The secondary macronutrients may be gas, upholstery, and oil. The micronutrients are the very small things, by volume that are still very critical for function – the sparkplugs, brakes, keys. It's not a perfect analogy but it gives the general idea that a plant's body, like a car, has some components in huge amounts, some in medium, and some in tiny amounts.

Table 3. Difference between what the soil can provide and what the plant needs

Macro- nutrients	% in typical soil	% in typical plant (%DM)[B]	difference	Exchangeable - available
N Nitrogen	0.1	1-3%	3%	lowest
K Potassium +1	1.5	0.3 - 6%	1%	low
Ca Calcium +2	0.5	0.1-3.5%	1%	medium
P Phosphorus	0.06	0.05-1.0%	1%	low
S Sulfur	0.05	0.05-1.5%	1%	medium
Mg Magnesium +2	0.4	0.05 - .07%	abundant	high

The soil never seems to be able to keep up with the nitrogen demands of plants. Plants need a lot compared to what's "in" a typical soil. We'll examine the N cycle in the next paper. On the bottom of the Table is Mg; it is more abundant in soil than what a plant needs. There are a few exceptions, but mostly farmers do not supply Mg or any of the other micronutrients because there is enough in the soil.

Why is Ca considered a secondary macronutrient when it looks like plants have more of that in their body than phosphorus? The answer has to do with the amount of each of those nutrients the soil can provide compared to how much is in the plant body. Review the table's last column "exchangeable–available" to see why calcium and sulfur are considered secondary macronutrients while potassium and phosphorus are primaries. It turns out that there is not much "exchangeable-available" K or P for plants in the soil because of soil chemistry. Clay and other soil particles "grip" the +2 Ca and +2 Mg more than the +1 K. The K slips away via leaching and therefore needs to be replenished by fertilizers. The Ca & Mg are held and "time released" when they become depleted in the soil solution. On the other hand, the anion -2 Phosphorus can be gripped *too* tightly by adsorption onto soil particles. The phosphorus needed for plant growth may be limited unless fertilizers are added. Sulfur seems to act more like Ca and Mg and is more available than P. That's why it is viewed as a secondary nutrient as well.

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Nutrient Cycling of Anions in the Soil.

The Elusive Case of Nitrogen.

You've read a little in the previous papers about the cation exchange capacity of soil and how the nutrients K, Ca, and Mg are made available to the plant. Now let's explore how the anion nutrients, especially Nitrogen (N), behave in soil and how the plant can access them. Rather than "exchanging" the major anions N, P, and S are considered to "cycle" through the soil in various forms.

Nitrogen (N). Nitrogen is not very abundant in soil but it is a relatively large component of the plant body. Plants remove nitrogen from the soil and concentrate it in their tissues. Nitrogen needs to be replenished whenever annual crops (except legumes) are grown because they remove nitrogen from the system.

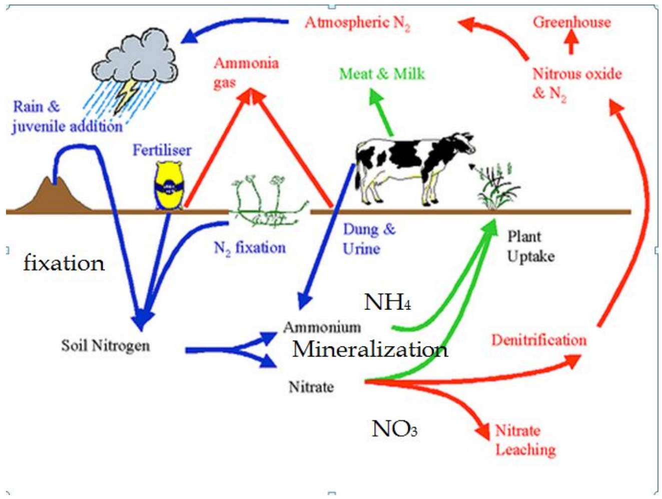
What **role** does nitrogen play in the plant? The presence of nitrogen is the defining characteristic of all proteins. You've probably heard of amino acids, these are simply some basic nitrogen containing molecules that are building blocks of even more complex molecules called proteins. This is why nitrogen is in such demand by both plants and animals. It is a foundation of all proteins, and thus all life. It is not synthesized from the air (except by bacteria in the nodules of legume plants) or water. Nitrogen is usually not a limiting factor in normal, everyday plant growth; but it is often limited in the high production and yield goals of modern agriculture, even sustainable agriculture.

Besides nitrogen there are two other anionic macronutrients plants require, phosphorus and sulfur. What is the relationship of the presence (or absence) of these anionic elements in the soil and their availability for the plant as nutrients? The availability is considered in the context of how they cycle from one form to another. Nutrient cycling of **anions** is complex compared with the availability of the **cations** which simply "exchange". We'll take a look at the nitrogen cycle to see all the forms this nutrient can take and just how complex it is to find out if plants have enough. After that, we'll review the implications of the cycle for nitrogen fertilizer and farming.

Nitrogen has a lot of options when it comes to forming compounds. It is simply looking for ways to feel stable and balance out that extra electron circling outer orbit. Chemically, relationship-wise, it's looking to be completed.

Shares electron(s) with:	Results in:	We call it	comments
Another N	N_2	Nitrogen gas	It's in the air. It makes up 78% of our atmosphere! Super stable triple bond takes energy to break.
Two oxygens	NO_2	Nitrous oxide	Potent "greenhouse" gas
Three oxygens	NO_3^-	Nitrate – a slippery molecule	If it is not taken up by plant roots it either leaves the soil as NO_2 gas or through leaching.
Four H's	NH_4^+	ammonium	Yummy form plants can take up via roots
Three H's	NH_3	ammonia	An intermediate form on the way to NH_4^+

The nitrogen cycle is a picture of the different ways and places that nitrogen exists.



The blue arrows above indicate ways that inert atmospheric nitrogen N_2 enters the biological system. The red arrows indicate ways that biologically available nitrogen leaves the plant/soil system.

1. Fixation. The process of converting N_2 to forms usable by plants. How? Three ways: a) nodules form with micro-organisms and roots in legumes b) lightening or volcanic eruptions provide enough energy to bind molecules of nitrogen together with oxygen or c) industrial manufacturing process which results in fertilizer. To "fix" nitrogen requires energy and that is why it's an expensive fertilizer. At any one time, 99% of the soil nitrogen is in a this fixed, organic form.

2. De-nitrification. Soil nitrogen converts back to N_2. There are a variety of ways denitrification occurs. Both have to do with water. Rain water can leach the "slippery" nitrate molecules out of the soil and into the groundwater. Nitrogen can also volatilize; it leaves the soil and re-enter the atmosphere.

These two processes above, fixation and denitrification are always in balance. More sub-cycles occurring in the soil that are outlined below:

3. Mineralization: fixed, organic nitrogen becomes *available* nitrogen to the plant as Ammonium (NH_4^+). About 2-3% of organic nitrogen becomes mineralized in a year. One complete "turn over" of soil nitrogen occurs then every 30-50 years. Mineralization is also called ammonification because it first becomes ammonia (NH3) which then continues its' transformation into ammonium which plants use.

4. Nitrification: process by which NH_4^+ produces available nitrogen as the nitrate (NO_3^-) anion. Nitrification results in the production of H^+ ions and can increase soil acidity (lowers pH). Nitrates are stable in well aerated soil, but leach easily out of wet soil because they combine with H_2O and run away together.

5. Uptake or immobilization: Plants take up both NH_4^+ and NO_3^- through their roots and incorporate it into their bodies. The nitrogen becomes immobile because it is "stuck" in the body of a plant.

Implications of the nitrogen cycle. Most people don't realize that we are surrounded by an atmosphere full of nitrogen. The air we breathe is 78% nitrogen gas, N_2. This nitrogen gas is really very inert because it is triple bonded to itself. It (N_2) doesn't want to transform into a biologically available form of nitrogen. If only we could get that nitrogen into something we can use to grow plants then life would be wonderful, right? How does N_2 from the air become bio-available? Well, in a natural system nitrogen is fixed one of two ways. One way it is fixed is by the incredible, tiny, fantastic little bacteria (Rhizobia) associated with root nodules of plants in the legume (and other) families. There are also some other kinds of free-living bacteria that fix nitrogen. A second (minor) way is with a massive injection of energy – lightening, or volcanoes. The heat energy in lightening causes the N to combine with oxygen to form compounds that fall to earth in the rain.

The third way nitrogen gets fixed is synthetically, by humans. We use energy from fossil fuels to power the reaction. Here is a short explanation from the website "How Stuff Works". "In this process, heated nitrogen (from the air) and hydrogen are mixed under very high pressure in a vessel where they combine chemically. The vessel contains a catalyst (usually iron with oxides of aluminum and potassium), which speeds up the chemical reaction. The Haber process is the most widely used process for the commercial production of ammonia. Fritz Haber, a German chemist, developed the process in the first decade of the 20th century. Karl Bosch, another German scientist, adapted the process for industrial use." This is the Haber-Bosch process. As a side-note, Fritz Haber was also a nazi war criminal. Is the Haber-Bosch process a blessing (feeds a lot of people) or a curse (significant degradation of the environment)?

Demand by plants to build proteins is why synthetic nitrogen fertilizers are the most heavily used type of fertilizer in conventional agriculture. Because plants (and resulting milk and meat) are removed from a farm by harvest, nitrogen is removed and must be replaced. Synthetic nitrogen is quite expensive and energy intensive to manufacture. It is an "unnatural" addition to a plant-soil-atmosphere system that was balanced at one time. What we've done is take a stable N_2 atmospheric molecule, break it apart, feed some of it to plants as fertilizer, and let the rest escape the soil cycle as either nitrous oxide greenhouse gas or nitrates leached into our waterways. Industrially fixed nitrogen is something new on the earth. We've doubled the amount of fixed nitrogen previously in the cycle. We now add over 10 million tons of NO_2 to the atmosphere annually. As non-organic corn production rises – so will our synthetic N production and its transformation and escape into the atmosphere and into our groundwater. Humans have become an important factor in the nitrogen cycle.

It is estimated that up to half of the nitrogen conventional farmers apply to their corn crops is lost from the system by leaching or denitrification. In high corn yield areas it is not uncommon for farmers to add 200 lbs of synthetic nitrogen per acre to a corn field. They add it at somewhat lower or higher levels according to the price of the N fertilizer. Right now, in 2016, N fertilizer is relatively cheap because of the fracking boom in natural gas and the cheap energy costs. But if 200/lb/A is added, and only half of that is actually used by the crop, the other 100 lbs/A runs out of the system and into the environment. This is a cost externalized to all of us.

Organic farming and the nitrogen cycle.

Organic farms are not allowed to use synthetically produced sources of nitrogen like urea or synthetic ammonium. In fact, this restriction is probably what prevents a majority of regular crop farmers from becoming certified organic. They just can't imagine cropping without their synthetic N.

So how do organic farms get nitrogen into the soil? What are the organic options for nitrogen? There are organic fertilizers that can be purchased, but most organic farmers choose to "grow their own" nitrogen.

A "per acre furrow slice" of soil contains about 1000 lbs. of nitrogen for each 1% of organic matter, but as we have learned, most is in the fixed form. There will be about 20-30 pounds of nitrogen mineralized each year for each 1% organic matter in the soil. A 150 bushels of corn/A contains 235 pounds of nitrogen incorporated into plant tissue itself. The natural sources of nitrogen in many conventional soils is small compared to the needs of industrial corn. Where will the organic farmer get the 200 lbs. of nitrogen needed to grow 150 bushels of corn?

Soils with high amounts of organic matter may supply almost enough nitrogen for a high yielding corn crop. For example, a soil with organic matter of 3.5 percent may contain 3,500 lbs. of Nitrogen per acre. It will mineralize or make available about 105 pounds of nitrogen per acre. Organic farmers seek to increase soil organic matter as a means of increasing the nitrogen available to their plants.

The nitrogen supplying power of a soil is intimately related to the organic matter and mineralization rates of a soil.

Organic farmers tend to supply their most of their nitrogen needs by using biological processes rather than synthetic processes. Organic farmers "grow their own" nitrogen in a variety of ways; animal manures, green manures, and cultivating the mini-livestock in the soil, the nitrogen fixing bacteria and the worms and soil biology. The bottom line, organic farmers grow nitrogen by harvesting it from the atmosphere rather than purchasing nitrogen when possible.

Also, organic farms loose very little nitrogen from the system or soil cycle due to denitrification, leaching and volatilization. Organic nitrogen is slowly released and steady. It is not lost from the system and is therefore available to the plant.

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