The author examines soil structure during the '01 Kansas No-Till Tour. During these forays, Ward is always armed with his trusty spade and his quick wit.

Soil Organic Matter and N Cycling

by Ray Ward

SCIENCE

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There are a lot of questions about fertilizers, fertilizer application, and plant nutrition. To address some of these questions, I thought I would discuss some of the basics of soil fertility and soil chemistry. Since carbon (C) is the largest nutrient required by a growing plant, and N is second, I will discuss those relationships first.

Soil organic matter (OM) is the *decomposed* plant residues and microorganisms. The pieces of plant material you see on the soil surface either from the last harvest or from several years ago is crop residue, not soil organic matter. The real carbon sequestration occurs in the decomposed plant residues.

The stable organic matter in the soil has a carbon to nitrogen (C:N) ratio range of 10:1 to 12:1. One percent organic matter is the same as 10,000 pounds of OM per 1,000,000 pounds of soil. Since one inch of soil across one acre weighs about 300,000 pounds, an 8-inch layer of soil containing 1% OM is the same as 24,000 pounds of OM. This is 12 tons of OM. If a soil has 3% OM in the top 8 inches of soil then there are 36 tons per acre.

Organic matter is 58% carbon, which is almost 21 tons of carbon per acre in those 36 tons. So with a C:N of about 10:1, if there is 21 tons of carbon then there is 2.1 tons of organic N or 4200 pounds of organic N per acre in an 8-inch layer of soil. How much of this organic N is available to a crop in one year? In the days of conventional tillage we considered the following as useful guidelines for a soil with 3% OM (i.e., 4200 lbs. organic N):

for small grains: 1% release per year (42 lbs of N)
row crops: 2% release per year (84 lbs of N)
summerfallow: 4% release per year (168 lbs of N)

With tillage a considerable amount of organic nitrogen was released per year, and the variation in the above figures is due to the timing and extent of tillage and the timing of the crop's growth. One of the reasons for summerfallowing was mineralization of organic N to nitrate. As the N was released, carbon was lost as carbon dioxide (CO_2). Therefore as we continued to cultivate the land we lost organic matter. Turnover in undisturbed grasslands is much slower, at about 0.5% release per year (21 lbs of N).

An Empty Warehouse?

Why is soil OM important? As I described, it is a 'warehouse' for N storage, as well as other nutrients, which are slowly released or 'spoon-fed' to the crop under no-till. Soil OM also improves the water-holding capacity of the soil, as well as the physical properties of the soil which will be discussed.

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As no-tillers try to build organic matter in the soil, one must remember that N has to be sequestered also. By leaving residue on the surface it is hoped that OM will build. How does this happen? When crop residues are incorporated by tillage, the microorganism population increases very rapidly. If there is good moisture, warm temperatures, and available nitrate, decomposition is complete in a few short months. *(Editors' Note: The atmospheric oxygen introduced into the soil by tillage allows the population explosion of decomposing organisms, which need the oxygen for respiration—their 'feeding frenzy' typically oxidizes more C than what the crop accumulated during the season.)* Tillage also decreases the size of aggregates (granular clumps of soil), allowing microorganisms more access to carbon inside those aggregates. Therefore, tillage over a period of 50 to 60 years released carbon (and other nutrients) that had taken dozens of centuries to accumulate. By leaving the soil undisturbed we begin the process of building OM. However, for every 10 pounds of carbon trapped, one

Ward in his natural habitat. He developed and managed several different soil labs in various states before founding his own at Kearney.

pound of N must be trapped. This will take a very long time because we are applying just enough N to meet crop needs. It does *not* imply that we can build OM just by over-applying N. The problem is surface residue and solubility of nitrate: An inch of rain will move extra nitrate away from the residue with the possibility of it moving through the root zone if not used by the growing crop. Building soil OM can best be done simply by managing for high-yielding crops under permanent no-till, using N fertilization methods that are efficient for plant growth and application.

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Getting back to the old guideline of N release from organic matter. It was the method we used to estimate N availability before we started using nitrate soil testing. This shows how the pioneers were able to grow good crops without N fertilizer: it was supplied by the OM. As tillage continued, organic N was mineralized until equilibrium was reached where very little OM was being mineralized. That is when farmers on the Great Plains started using N fertilizer.

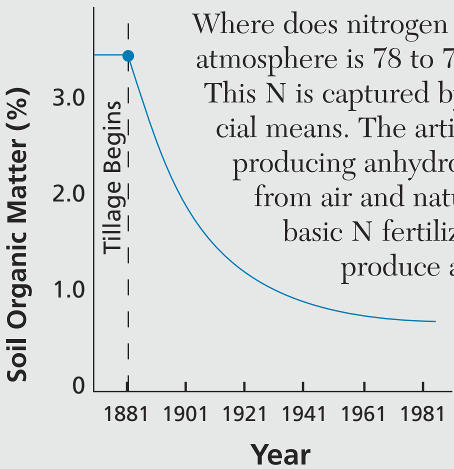
Recovery

Why does the soil in no-till seem like it has a lot more organic matter even though the OM soil test is increasing very slowly? Leaving residue on the surface increases soil biology. High residue favors increased earthworm activity. This activity increases water infiltration, reducing water runoff. In addition, residue on the surface reduces water evaporation, allowing the soil to remain wetter for a longer period of time. Microbe populations thrive with better moisture and a constant supply of food (residue). Compounds produced by the microorganisms bind soil particles together to form aggregates. Some of the 'glue' is water-stable so the aggregates remain intact during rainfall; however, residue must remain on the surface to protect the aggregate from raindrop splash.

Surface soil structure improves quickly when no-till is adopted, and we see great benefits in 3 to 4 years. The improved soil structure is noted by the no-tiller, who assumes OM is increasing (it probably *is* increasing, but at a rate too low to reliably be detected in soil tests; it may also be increasing at depths greater than are typically sampled for OM, if rotational changes occur which include more deeply rooted crops).

Improved soil structure in no-till also helps to retain nitrate-N. The nitrate ion can migrate inside of the aggregate. Water flows through the soil in the macropores between the aggregates. Since much of the nitrate is 'protected' in the aggregate, it is less subject to leaching as water infiltrates the soil.

From Thin Air



Where does nitrogen come from? The atmosphere is 78 to 79% nitrogen gas. This N is captured by natural and artificial means. The artificial method is producing anhydrous ammonia (NH_3) from air and natural gas. NH_3 is the basic N fertilizer that is used to produce all other commercial N fertilizers.

The natural means include N fixation by symbiotic and non-symbiotic (free-living) microorganisms. Certain bacteria (such as *Rhizobia*) in relationship with legume crops can carry out symbiotic N fixation. These bacteria infect the root hairs and establish colonies or nodules on the roots. The *Rhizobia* fix N for the plant and the plant feeds the bacteria from the photosynthate produced by the leaves: a symbiotic relationship. Each legume has a specific *Rhizobium* symbiont. It is interesting to note that the artificial and natural processes do the same thing: taking atmospheric N_2 gas and converting to NH_3.

Growing high-yielding crops is one of the key steps to building and maintaining soil OM.

Free-living, non-symbiotic N-fixing microorganisms are able to fix N from the air without living with another plant. The annual supply of N contributed by non-symbiotic fixation probably amounts to a maximum of 6 pounds of N per acre per year. This estimate is based on cultivated agriculture. There is some research that indicates we can expect 2½ times more N to be fixed by non-symbiotic microorganisms in a no-till system. By developing a more vibrant population of microorganisms in no-till, we can expect to continue to improve N fixation. There is potential to sequester more carbon when we have an increase in fixed N from the microbes. As we use more cover crops, especially legumes, we will see an increase in N availability.

A small amount of N is also added to the soil through rainfall. Rough estimates say 4 to 7 pounds of N per acre are added annually.

Photo by Matt Hagny.

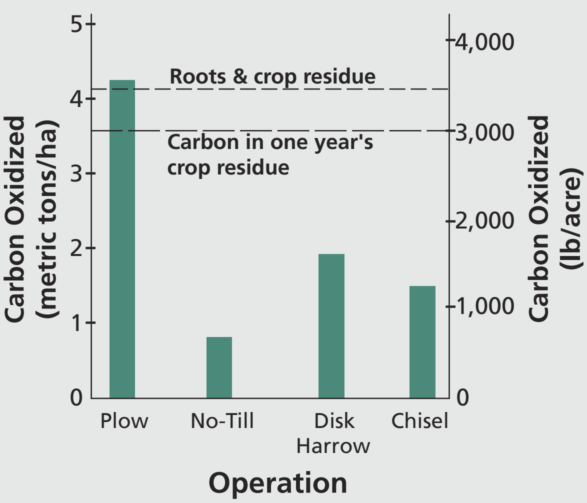
Permanent no-till is the other vital ingredient for increasing soil OM. Good structure in the soil is another by-product of leaving it undisturbed. Note that the mulch on the surface is not soil OM, nor will all of it become soil OM. Stable soil OM is formed of decomposed plant residues and microbes during a lengthy process. Tillage disrupts the balance by letting the microbes on the soil surface have too much plant residue and oxygen all at once, which they quickly consume, releasing all the carbon as CO_2 during respiration.

Legume crops have a higher concentration of N, which is reflected in their greater protein content (N is a component of protein). The C:N ratio of legumes is generally less than 20:1, which is equal to crude protein content of greater than 12%. Therefore, legumes start releasing nitrate as soon as decomposition begins. This is the reason that legumes have long been considered a source of soil fertility.

Corn stalks have C:N of about 70:1 (about 5% crude protein), and wheat straw also has C:N of approximately 70:1. As the residue begins to decompose, the microorganisms immobilize nitrate-N. In general, small grain straw and corn stalks 'tie up' from 18 to 30 pounds of N *per ton* of residue. After 3 to 4 years of no-till the decomposition of old residue is such that additional N is not needed. As decomposition proceeds further, nearly all the N that was initially immobilized in the small grain, corn, or milo residues will be mineralized (released). If only corn, milo, and small grains are rotated, the soil will have a rough equilibrium of immobilization by new residues and mineralization from old residues.[1] However, any legume in rotation will make mineralization dominate the equation while that residue is decomposing.

From Stubble to OM

What happens to N when crop residue and N fertilizer are added to the soil? If the crop residue has a C:N ratio of greater than 30:1, the microbial population will use any available soil N to decompose the residue. This process is referred to as immobilization of N. On the other hand, if the C:N ratio of crop residue is less than 20:1, the microbial population will begin releasing available N as soon as decomposition starts. This process is referred to as mineralization. *(Editors, again: The microbes decomposing the residue aren't the same type that fix N.)*



Carbon oxidized in *19 days* in September following various tillage operations on wheat stubble in Morris, MN, from measured CO_2 emissions.
Source: D. Reicosky and M. Lindstrom, 1993.

What is happening to make the C:N ratio go from 70:1 down to 20:1, and eventually down to 10:1 in soil OM? The microbes are using the residues as a food source, and respiring CO_2 and so only a very small percentage of surface residues becomes soil OM. A much larger percentage of crop roots ends up as soil OM, even though root biomass is typically less than the aboveground portion for most annual crops. Note that the C:N ratio can be narrowed by either a substantial oxidizing of carbon by the microbes, or by the acquisition of additional N, typically organic N.

N for Crops

Mineralization is the conversion of organic N to plant-available N ('organic' here means compounds containing C, 'plant-available' refers to NH_4 or NO_3). The process includes ammonification and nitrification. The controlling process is ammonification. If ammonium compounds are not produced then nitrification (the production of nitrate from ammonium) will be zero. Ammonification is able to

[1] N fertilizer is still required to grow the crop and to replace what is removed from the field in grain, as well as any other losses from the system (leaching, denitrification, etc).

Photo by Tom Will.

Dwayne Beck describes the fact that corn does exceptionally well following certain cover crops. This probably has something to do with creating elevated CO_2 levels in that corn canopy as the legume decomposes. Also because the legume N is naturally 'time released' or synchronized with corn root growth, and more dispersed through the profile. Additional biological reasons may exist.

continue under waterlogged conditions; therefore it is less affected by waterlogging than nitrification. Nitrification requires oxygen. If oxygen is low in the soil, nitrification will be low. Plant roots can take up the ammonium (NH_4) directly, before it converts to nitrate (NO_3), although if oxygen levels are too low to form nitrate then root growth will also be restricted. But as far as the plant is concerned, nitrate is nitrate and ammonia is ammonia—the plant cannot tell the difference between those N molecules derived from mineralized OM or from fertilizers or from legume fixation.

The optimum soil temperature for mineralization is between 77 and 95 degrees F. Below this temperature, mineralization gradually decreases and practically stops at or near the freezing point. This is why soils in the Dakotas accumulate and retain OM more easily than soils in Kansas or Oklahoma.

Partial sterilization of the soil also has an effect on rate of mineralization. Nitrate production is more rapid after the soil has been partially sterilized by drying or by freezing and thawing. This partial sterilization may account for the high rate of mineralization of nitrate-N in early spring or after a prolonged drought.

Early in the article I gave an example of estimating available nitrogen for different crops based on cropping practice and soil OM. In no-till we don't disturb the soil so the rate of release should be near the rate of undisturbed grasslands. When we hear about tilling land that was no-till, we can assume that we will get a tremendous release of available N from the organic N on or very near the soil surface. However, it will only take one year to release most of this N from the organic matter and then the process will have to start over again. The short-term benefit could be very costly to future cropping.

The microbes are using the residues as a food source, and respiring CO_2. So only a very small percentage of surface residues becomes soil OM.

From purely the standpoint of cycling N from soil OM, then, there is no reason to move to no-till. Those reasons are found elsewhere, such as improved moisture storage and usage, improved plant health, reductions in equipment and labor, etc. Even that is an oversimplification. The N being released from OM under no-till will be primarily temperature-dependent, since that is the limiting factor for mineralization in that system. Because crop growth is also temperature dependent, mineralization and crop uptake are closely matched, resulting in fewer losses. In a tillage system, mineralization is primarily influenced by when the tillage is done, which is typically long before planting the crop. Therefore, there is more chance for mineralized N to be leached or otherwise lost from that system. Soil and nutrients lost in runoff make the tilled system even more inefficient.

In future articles I will take up the problem of predicting N fertilizer requirements for a crop, as well as sources and methods for N fertilization and how those might differ in no-till compared with tilled systems.

Editors' Note: Very few people, scientists included, think of carbon as an essential plant nutrient to be managed as such. Dwayne Beck reminds us of this, noting that most greenhouses fortify their air with CO_2 to enhance plant growth. Managing the cycling of carbon in the context of no-till field crops is a new concept—basically sequencing the crops or timing the N applications to match CO_2 emissions from decaying residues with crop canopy conditions. Cycling nutrients is nothing new, but everyone forgot about the most important nutrient, carbon. Beck remarks playfully: "That's why we have Dwayne Beck around—to talk about the obvious stuff."

Photo by Matt Hagny.

Rebuilding soil OM requires plants to accumulate carbon from the air, but also N must be acquired from somewhere. That N comes from the atmosphere by several routes: 1) from fertilizers synthesized from reacting natural gas with the air (under heat and pressure), 2) from N fixed by free-living organisms in the soil, and 3) from N fixed by bacteria living symbiotically on the roots of legume plants, such as this sunn hemp.