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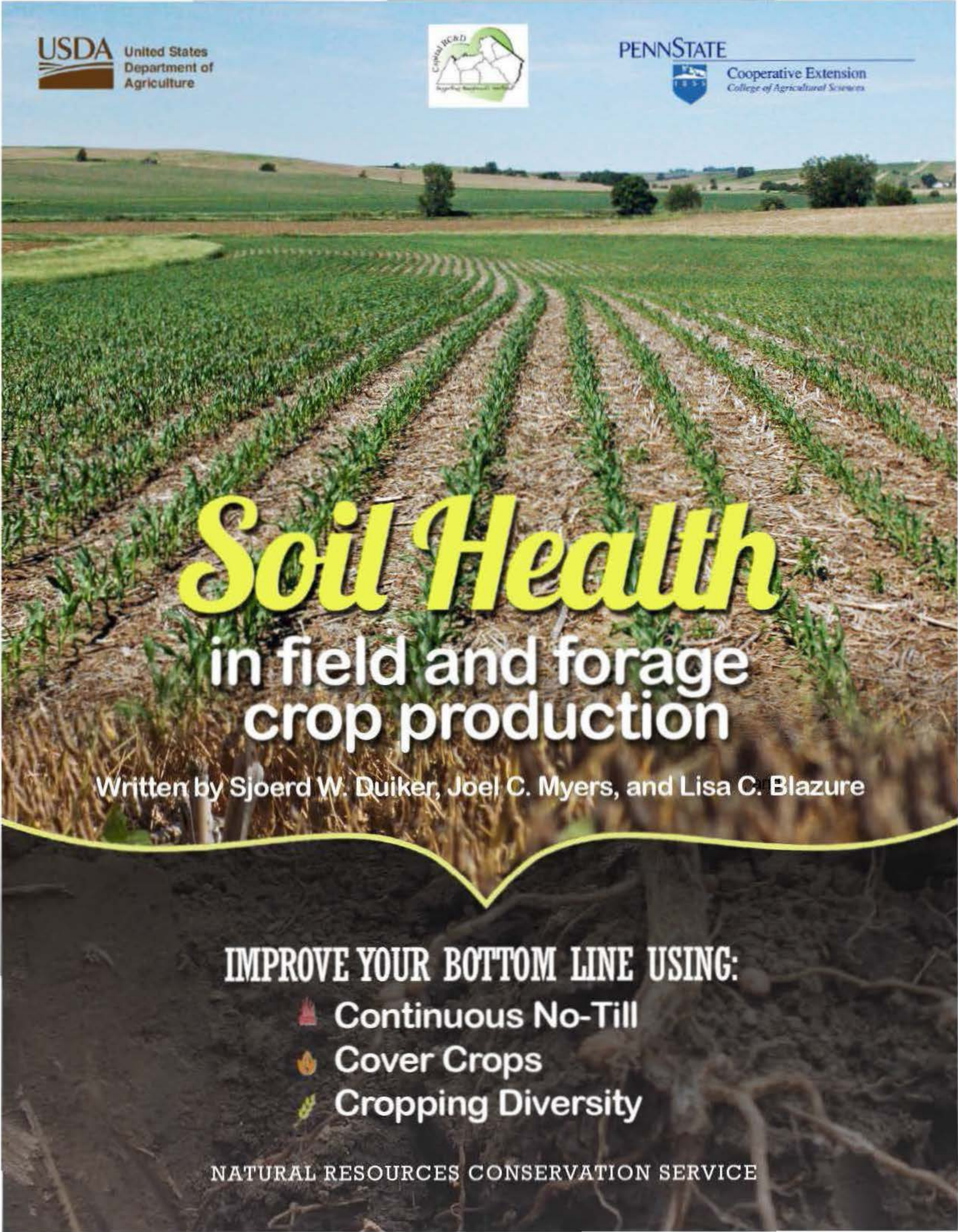

Soil Health
in field and forage crop production

Written by Sjoerd W. Duiker, Joel C. Myers, and Lisa C. Blazure

IMPROVE YOUR BOTTOM LINE USING:

- Continuous No-Till
- Cover Crops
- Cropping Diversity

NATURAL RESOURCES CONSERVATION SERVICE

This publication is a combined effort among partners at the USDA Natural Resources Conservation Service, Penn State University Extension, Capital Resource Conservation & Development, and Clinton County Conservation District

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Contents

Improving Soil Health in Field and Forage Crop Production

Soil health is the continued capacity of soil to function as a living ecosystem that sustains plants, animals, and humans. Viewing soil as a living ecosystem that has 'health' reflects a fundamental shift in the way we think about soil. Soil isn't an inert growing medium that needs to be filled up with water and nutrients when it runs out. Rather, if the soil is healthy, it is teeming with large and small organisms that live together in a dynamic, complex web of relationships. Farm crops and animals become part of this unique 'cycle of life.'

A healthy soil enables a cropping system to run smoothly, just like the well-oiled hub of a wheel. In contrast, a 'sick' soil has an ecosystem that is out of balance, lacks certain key organisms, or lacks the food these organisms need. This results in problems such as low yield, increased runoff, soil moisture deficits, pest and disease problems, and nutrient deficiencies. In the past, it was common to treat the symptoms of poor soil health with temporary patches. For example, runoff problems might be dealt with by tilling the soil to increase pore space, not realizing that the fundamental problems were lack of soil armor (i.e., cover) to protect the soil from raindrop impact, absence of continuous living vegetation to capture solar energy to feed soil organisms which create spongy soil structure, and a living root system that stimulates aggregation!

Soil health is like the hub of a wheel, while continuous no-till is the rim.

Lack of soil health is usually the reason farmers, researchers, and policy makers struggle with no-till. If soil is healthy, success with no-till is achievable and problems such as the excessive use of pesticides or nutrient runoff are avoided. Considering the negative impacts of tillage on soil health, this publication takes the view that continuous no-till is needed to achieve soil health. Continuous no-till is the planting of all crops without the use of any prior tillage.

This publication emphasizes the natural principles of the no-till system. Soil health is like the hub of a wheel, while continuous no-till is the rim *(Figure 1, page 2)*. We will discuss 14 spokes connecting the hub and rim.

These 14 spokes are management principles and techniques to improve soil health:

1. Diversify Crop Rotations
2. Plant Cover Crops
3. Diversify Cover Crops
4. Maximize Living Roots
5. Grow Living Plants
6. Manage Carbon
7. Use Interseeding
8. Plant Green
9. Enhance Soil Armor
10. Manage Nutrients
11. Manage Manure
12. Manage Pests
13. Avoid Compaction
14. Integrate Crops and Livestock

Photo: Kelley King, King Photography

Figure 1. Soil health is like the hub of a wheel. There are 14 spokes, or management principles and techniques that improve soil health.

When spokes are missing, the wheel starts to malfunction, but when they are present, the system is highly productive, profitable, and environmentally sustainable. This publication explains how to build soil health, increase profit from a diversity of enterprises, reduce risk by weather-proofing crops against extremes in rainfall and temperature, protect crops from pests and diseases, and utilize animals as an integral part of the farm.

Soil Biology

Nematodes

Photo: Soil and Water Conservation Society (SWCS). 2000. Soil Biology Primer. Rev. ed. Ankeny, IA.

Nematodes are often known as pests to agricultural crops, but most nematodes do not cause crop damage. Nematodes eat bacteria, fungi, protozoa, pest nematodes, and insect larva. Like the protozoa, they also excrete nitrogen and micro nutrients in a form that is plant available.

Worms

While not exactly microbes since they can be seen with the naked eye, worms play an important role in agricultural fields and should be included in soil biology discussions. There are three main groups of worms: surface residue feeders (red wigglers), soil feeders (earthworms), and residue feeders that live in vertical burrows (night crawlers). The last two groups play a critical role in water infiltration because their channels and burrows allow water to soak into the ground. Plant roots also tend to grow into these open channels. The slimy worm excretions help build soil aggregates and contain plant available nutrients. Night crawlers are long lived and are typically rare in tilled fields.

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Protozoa

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These single-cell organisms are the grazers of the microbe world. They move freely in the water around plant roots and soil aggregates. They feed on bacteria, fungi, and algae. As they eat other microbes, they excrete nitrogen and micro nutrients in a form that is immediately plant available.

Bacteria

These are the smallest of the microbes and the most abundant. They utilize simple sugars from the plants and digest food sources like dead plant cells and cellulose. Some bacteria have the ability to turn atmospheric nitrogen into plant-available forms. Rhizobia bacteria associated with legumes are the best known of these bacteria, but there are other types of free-living soil bacteria that can also fix nitrogen. Bacteria are a food source for the other microbes. Plowed fields and grass systems tend to have higher populations of bacteria than fungi.

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Fungi

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There are two main groups of soil fungi: one group breaks down organic material and the other group (Mycorrhizae) forms a large underground network that connects to plant roots and scavenges nutrients and water for the plants. Both types are important for building humus and breaking down complex plant materials like corn stalks. Fungi also produce a biotic glue (called glomalin) that is critical to forming soil aggregates and creating good soil structure. Continuous no-till soil will have larger fungal populations than plowed soil.

Continuous No-Till for Soil Health

No-till is a powerful tool to combat erosion. It increases residue cover and creates firmer soil and better soil structure. No-till reduces erosion by more than 80 percent versus chisel plowing in a corn-soybean rotation where crop residue is left after harvest. Even if some crop residues are removed in this rotation, soil erosion is still reduced more than 70 percent by using no-till. In continuous silage corn, the addition of a cover crop can decrease erosion by as much as 70 percent, whereas the removal of soybean residue can increase erosion by as much as 25 percent.

Instead of addressing soil erosion and soil degradation, there is a need to focus on building soils. Keeping growing crops on the landscape throughout the year, including cover crops with continuous no-till, can reduce soil erosion to very low levels. The soil building process becomes possible when soil loss is reduced to levels not reflected in current erosion prediction models.

Because it takes years to improve soil health, it is important that no-till is practiced continuously. Even one year of tillage can have a dramatic negative impact on soil health. A research study in central Pennsylvania showed the positive effect continuous no-till has on soil tilth. Soil aggregate stability in the soil surface of continuous no-till was 100 percent greater than in moldboard plow, 61 percent greater than in chisel/disk, and 25 percent greater than in short-term no-till *(Figure 2)*.

Because it takes years to improve soil health, it is important that no-till is practiced continuously.

Continuous no-till is defined as the planting of all crops without the use of any prior tillage. The no-till planter or drill accurately places the desired crop seed at the proper depth while providing good seed-to-soil contact. Planters and drills may or may not use coulters. They may be equipped with disk fertilizer openers to properly place plant nutrients. Shallow disk injection of manure or fertilizer is also considered to be consistent with continuous no-till planting. However, a focus on equipment would be self-defeating, no matter how important it is. This publication emphasizes the natural principles of the no-till system.

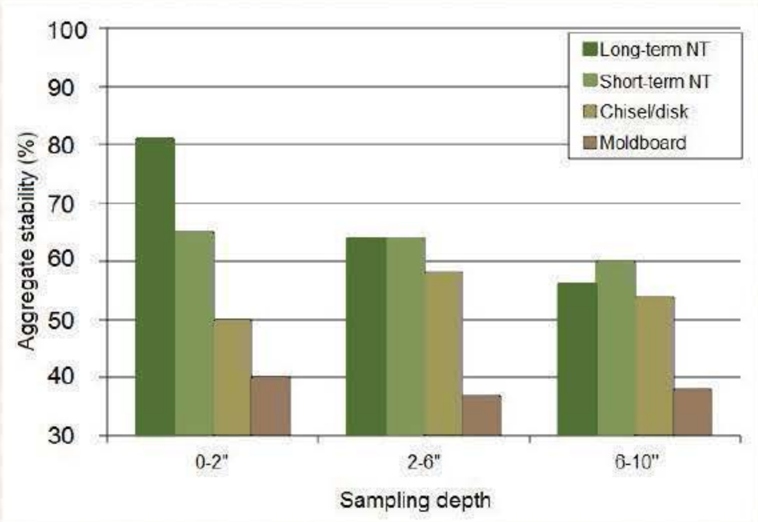

Figure 2. Building soil structure with no-till takes time. Aggregate stability in a long-term study was much higher in continuous no-till than in short-term no-till, chisel/disk, or moldboard plowed plots. *(Courtesy of Sjoerd Duiker)*

No-Till Soils

Soil aggregate stability is a measure of soil structure. Soil structure is the manner in which soil particles (sand, silt, and clay) are arranged and connected. Sometimes it is called soil tilth. In a healthy soil, the sand, silt, and clay particles are loosely connected, with plenty of pore spaces between them for water movement, aeration, root penetration, and biological activity to take place. Important substances that hold the particles together are glues produced by mycorrhizal fungi and bacteria, the fungal hairs made by different kinds of fungi, worm excretions and fine roots. If these are lacking, aggregate stability will be low. It is extremely important to have stable soil structure at the soil surface. This results in mellow (friable or loose) surface soil: the major reason planting gets easier allowing farmers to remove coulters and reduce down pressure on the planters after a few years in no-till. The stable surface soil structure also helps absorb and hold water in the root zone for improved water and nutrient uptake and retention and eventually, increased yields.

A recent review of different studies shows that the longer no-till is practiced, the larger the microbial biomass becomes *(Figure 3)*. These microbes are an important indicator of soil health. Some of these microbes, especially fungi, are highly sensitive to tillage. Tillage is like burning down the house, it disrupts the microbial biomass and the soil biological community has to rebuild.

Soil improvement with continuous no-till is not limited to the surface. Annually plowed soil will usually show a dense plow pan just below the depth of tillage, the absence of deep burrowing earthworms, and weak surface soil structure. This contrasts with the soil profile of a high-quality, continuous no-till soil that has granular surface structure, blocky structure below the surface layer, absence of a tillage pan, and continuous macropores created by decomposing roots and earthworms which go from the surface deep into the subsoil. Therefore, continuous no-till modifies the entire soil profile *(Figure 4)*. Over time, continuous no-till soil begins to resemble a natural prairie soil.

Because of the firm but porous nature of long-term no-till soil, the soil supports weight without detrimental effects. This is very important for field work or when grazing animals. One study found that soil with poor structure was not trafficable for 25 days out of a wet, cold month, while the same soil with good structure was not trafficable for only seven days. This explains why grazing no-till cover crops seldom causes excessive compaction if managed properly. In a compaction study in Pennsylvania, rutting caused by manure spreader traffic decreased the longer no-till had been practiced *(Figure 5, page 6)*.

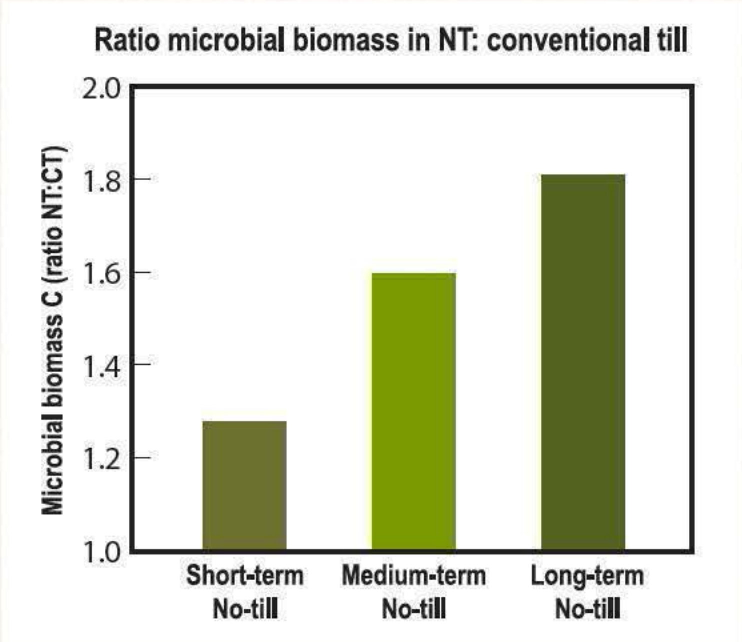

Figure 3. The ratio of microbial biomass carbon of no-till (NT) and conventional tillage (CT) for short term (0-2 yrs.), medium term (3-7 yrs.) and long-term (8-18 yrs.) no-till. It shows that microbial biomass increases the longer no-till is practiced. The samples were drawn from depths ranging from the top one to eight inches of soil and came from 40 different studies. *Source: Diva Souza Andrade, Arnaldo Colozzi-Filho and Ken E. Giller. 2003. The soil microbial community and soil tillage. Pages 51- 81 in Adel El Titi (Editor). Soil Tillage in Agroecosystems. CRC Press, Boca Raton, FL.*

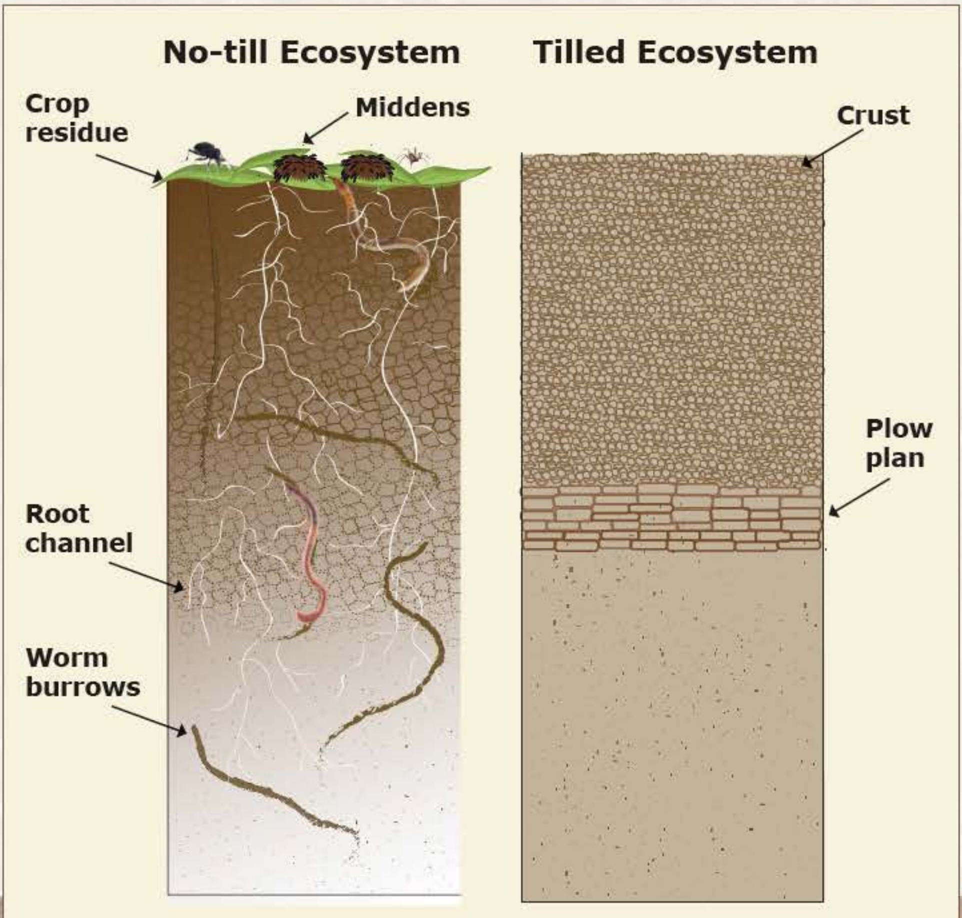

Figure 4. The entire soil profile will be modified when you use continuous no-till. The surface will be covered by mulch, granular aggregates, and earthworm middens. The topsoil will have a granular structure that gradually turns into a blocky structure with depth. The soil matrix is firm and yet the soil is perforated with thousands of pores created by roots, fungal hyphae, surface and deep-dwelling earthworms, and many other types of organisms. Old root channels and earthworm burrows leave pores that are continuous from the surface deep into the subsoil.

Long-term no-till soil resists compaction

Figure 5. A compaction study showed the difference in rut formation in a moist soil with a 30-ton manure truck with road tires in no-till of different duration. Long-term no-till had the least amount of rut formation, and ruts became increasingly deeper the shorter the time span became since the last tillage pass (tillage was done with a subsoiler to a depth of 17 inches). *(Courtesy of Sjoerd Duiker)*

No-till and Cover Crops in Pennsylvania

Since 2002, no-till adoption in Pennsylvania has increased, from just over 20 percent of planted acres to more than 60 percent today *(Figure 6)*. The statistics do not show whether no-till was used continuously, but presents a snapshot of no-till use in a particular year. However, an increase of continuous no-till is to be expected if more than 60 percent of the planted acres are planted using no-till. Unfortunately, the county transect surveys also show that 13-25 percent of the no-till acres do not meet minimum residue standards for erosion control. In addition, only half of the no-till acres had more than 50 percent crop residue cover after planting. This level of residue cover is considered minimum to maintain or increase soil health. There is still a lot of room for increased adoption of continuous no-till and better management to increase residue levels for soil health improvement.

Cover crops improve soil health. Cover crops are crops grown between two economic crops with the primary aim to protect and improve the soil. Cover crops reduce runoff, build soil organic matter, retain nutrients, fix atmospheric nitrogen, reduce and alleviate compaction, provide weed control, and improve soil health *(Figure 7)*.

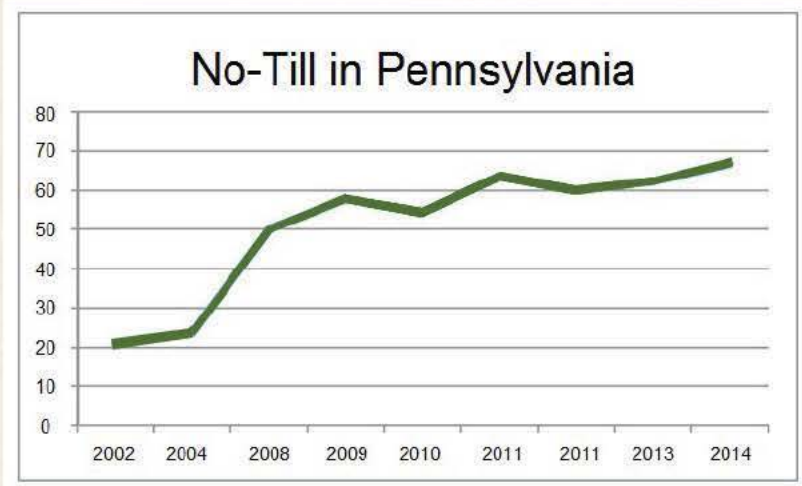

Figure 6. Percentage no-till of all planted acres in Pennsylvania over time as reported by USDA-National Agricultural Statistics Service in its annual tillage practices survey. The 2002 and 2004 data were published by the Conservation Technology Information Center and come from transect surveys performed by conservation professionals, while the other data are derived from a self-reported survey filled out by a sample of Pennsylvania farmers. It shows that no-till has been growing and is now the predominant crop establishment practice today.

Figure 7. Mixing cover crops from different groups in the cover crop periodic table provides multiple benefits for soil health and beneficials. This is a mixture of warm season non-legume broadleaves (buckwheat and sunflower), cool season legumes (austrian peas), cool season non-legume broadleaves (brassicas), and warm season grass (corn). *(Courtesy of Lisa Blazure)*

Cover crops can be used for livestock feed which may provide an economic benefit to farmers. This is an important consideration for Pennsylvania farmers. Cover crops can be grazed or harvested as forage, reducing the purchase of imported feed. This results in more nutrients cycled on the farm and reduced nutrient build-up in the soil. Although above-ground growth is removed when the cover crop is harvested, the root system stays in the soil. Root systems have been shown to be more important than surface residue to increase soil organic matter. Overall, using cover crops for feed is considered to be a win-win situation for farmers and the environment.

Cover crop statistics have been collected in the last two years in selected counties but are not yet gathered as part of a state-wide effort. In a 2014 transect survey in five counties, cover crop use varied from 22-37 percent of crop acres. This is a major increase over earlier estimates that suggested only 10 percent of crop acres were followed by cover crops. In a study done by the U.S. Geological Survey and Penn State University in south-central Pennsylvania, cover crop use after corn was estimated using satellite images. The images selected enabled the researchers to estimate cover crop use after corn crops in four counties by analyzing how green the fields appeared. The data suggest that cover crop use after corn increased from 40-66 percent over the years 2009-2013 *(Figure 8)*. Much of this cover crop acreage followed corn silage.

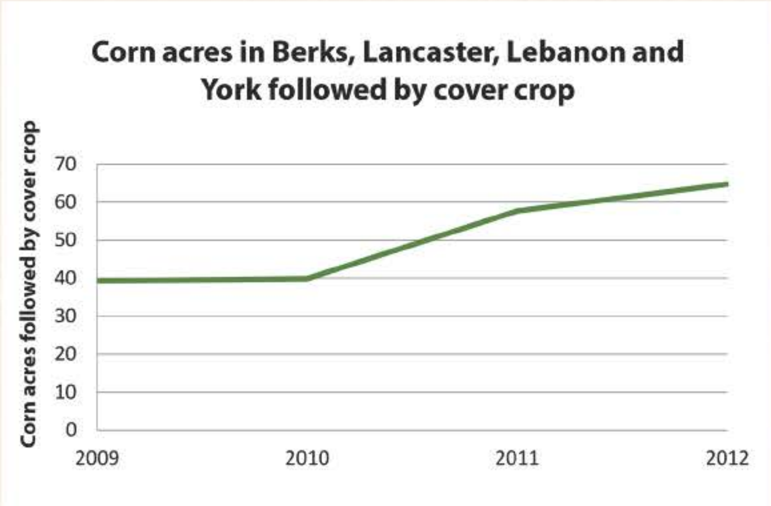

Figure 8. Percent corn acres followed by cover crop in Berks, Lancaster, Lebanon, and York as measured using remote sensing *(based on planted corn acres in 2012, from W. Dean Hively, Greg McCarthy and Sjoerd W. Duiker. Remote Sensing to monitor cover crop adoption in southeastern Pennsylvania. To be published in Journal of Soil and Water Conservation in December 2015)*

Management Principles and Techniques to Improve Soil Health

No-till works best when every spoke of the wheel is present. This section discusses each of the 14 spokes of the wheel that make up the hub of soil health, around which the rim of continuous no-till turns *(Figure 9)*. The spokes support the system and make it turn smoothly and able to sustain the load.

Photo: Kelley King, King Photography

Figure 9. There are 14 spokes, or practices, of the wheel that make up the hub of soil health, around which the rim of continuous no-till turns.

1. Diversify Crop Rotations

The first spoke is crop rotation diversity. Crop rotation is the 'repetitive growing of an ordered succession of crops on the same land over multiple years.' The first reason diverse crop rotations are important is that yields improve. Research from a long-term crop rotation trial in central Pennsylvania showed that, compared with continuous corn, corn yields were improved 7 percent when grown in rotation with soybeans, 15 percent in the first year after alfalfa/grass hay and 16 percent in a corn-oat-wheat-red clover hay rotation *(Figure 10)*. Interestingly, yield improvement of corn after alfalfa/grass hay was still present four years after termination of the hay.

The rotation effect on crop yield is well established agronomically (though not well understood) and confirmed in many different trials. Yet, it seems to be neglected. Why? It may be that agricultural systems have become focused on one or two crops due to high infrastructure and machinery costs. But, perhaps it is time to rethink this approach. Here are a few reasons why more diverse crop rotations are more beneficial:

Legumes in rotations fix atmospheric nitrogen through their symbiotic relationship with rhizobium bacteria and reduce the need for nitrogen fertilizer in the rotation. Part of the legume nitrogen can be counted as a credit towards the next, non-leguminous crop. Some legumes, such as peas, have been observed to have a very beneficial effect on following grass-type crops while terminated alfalfa sod supplies almost all the nitrogen required for a following corn crop.

Crop rotation is an important pest management tool. For example, corn rootworm is not an issue if corn is rotated with other crops. Weeds are also easier to control in a diverse crop rotation because of a range of practices to control them, such as narrow and wide row crops, winter and summer annuals, biennials and perennials, fertilizer placement (versus broadcast applications), different herbicide programs and application timings in the different crops, mowing, grazing, and harvesting at different times of the year. All these practices together work to reduce weed populations. By using diverse crop rotations in continuous no-till, herbicide use was reduced 50 percent compared with simple crop rotations on farms in the Great Plains.

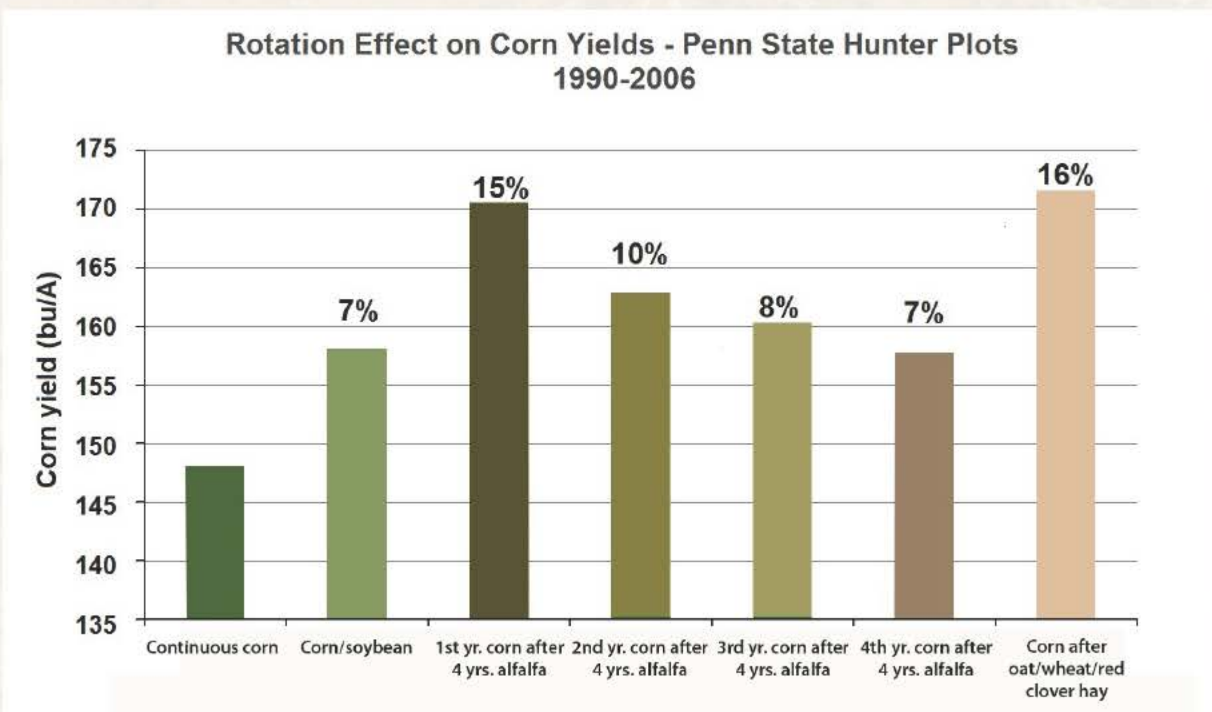

Figure 10. Crop rotation diversity increases crop yields as was shown in a long-term crop rotation trial on a Hagerstown silt loam soil in Centre County, PA. Percentages above the second to last bar indicate the percentage of corn yield increase over that in continuous corn (first bar). *(Courtesy of Scott Harkcom)*

Soil health is improved. Greater crop diversity above ground will also result in a more varied microbe food source and diverse microbial community below ground. Crops rotated with different root architectures, will impact soil structure in a variety of ways. Using massive, fibrous root systems will help improve aggregation, especially near the surface. The deep taproots of certain perennials can penetrate up to ten-feet deep. Old root channels will be available for subsequent crops, allowing for deep rooting and water percolation. In a long-term crop rotation trial in central Pennsylvania, aggregate stability was higher the more diverse the crop rotation *(Figure 11)*.

Machinery is used more efficiently. In simple rotations or monocultures, equipment is used only a few months in the year. With a diversity of crops that are planted and harvested at different times of the year, the combine, planter, and drill can be used more months of the year. It is also possible to use smaller, more affordable equipment.

There are fewer labor peaks. Labor needs are spread out over the year. Therefore, more diverse crop rotations also increase employment opportunities in rural areas.

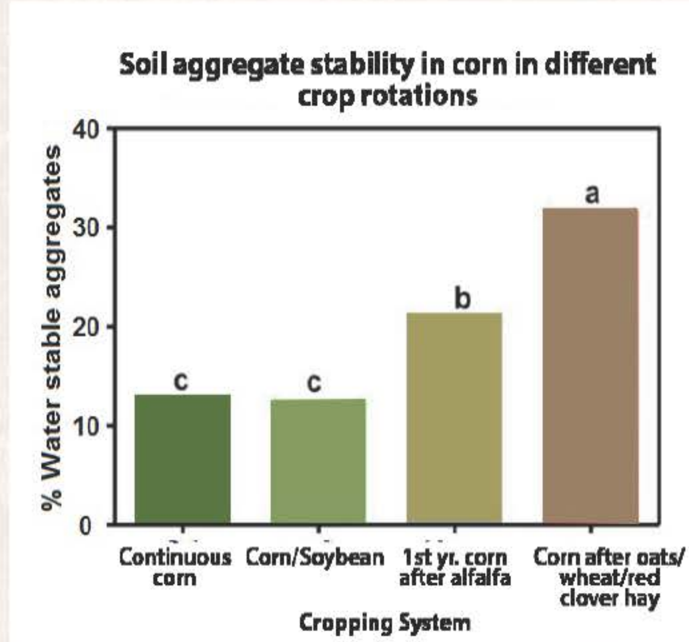

Figure 11. Aggregate stability was higher in diverse crop rotations in a long-term crop rotation trial in central Pennsylvania. *(K. K. Grover. 2008. Long-term cropping systems effects on soil aggregate stability, corn grain yields, and yield stability. A dissertation in agronomy. The Pennsylvania State University, University Park, PA)*

2. Plant Cover Crops

The second spoke is cover crops. Primarily grown for non-commercial purposes at times when soil would otherwise be without living vegetation, cover crops are used to:

Provide soil erosion protection. This is especially important if crop residue cover is minimal after harvest of the main crop.

Absorb, retain, and recycle nutrients. Some nutrients, such as nitrate, are soluble and can easily leach below the root zone. Cover crops take up soluble nutrients, protecting them from leaching. In a survey of cover crop biomass on working farms in different parts of Pennsylvania, every ton of dry matter (mostly rye) contained on average 57 pounds of nitrogen. Without cover crops, much of this nitrogen would have leached to groundwater and been lost to streams and rivers.

Maryland research confirmed that nitrate concentrations in soil water decreased remarkably when a cover crop of rye was used *(Figure 12)*.

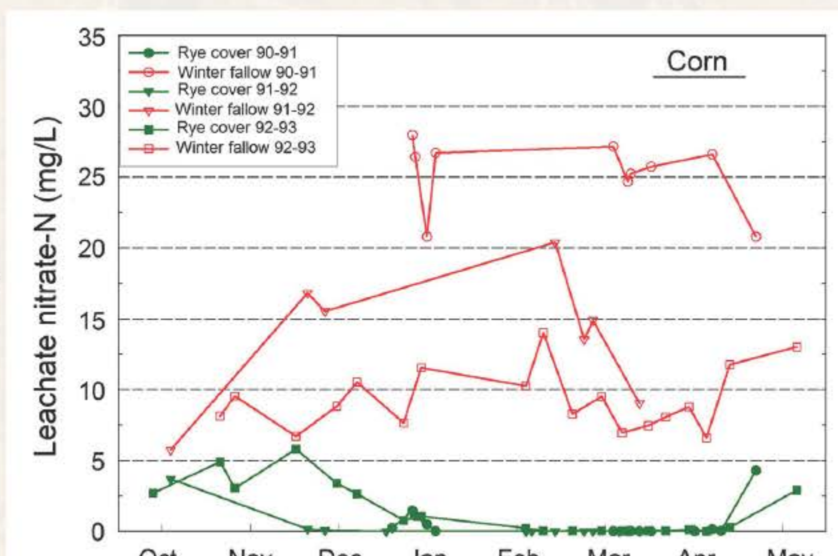

Figure 12. Nitrate-N concentrations in leachate decreased dramatically in Maryland when a rye cover crop was used. The rye effectively reduced nitrate losses to ground water and preserved N for future crops. *(K.W. Staver and R.B. Brinsfield. 1998. Using cereal and grain winter cover crops to reduce groundwater nitrate contamination in the mid-Atlantic coastal plain. Journal of Soil and Water Conservation 53(3): 230-240)*

Cover crops can make nutrients available from soil and release them to following crops upon decomposition. Some cover crops release organic acids that solubilize nutrients from soil particles. Research in Maryland showed that phosphorus was concentrated in the taproots of forage radish. Available phosphorus concentrations were increased where the root had decomposed in the spring *(Figure 13)*.

Fix atmospheric nitrogen. Leguminous cover crops fix large amounts of nitrogen from the atmosphere because of a unique bacterial infection in their roots that is beneficial to the legume and the bacterium. Because of this symbiotic relationship, no nitrogen has to be applied to these crops. The bacteria are called rhizobium, and different legumes are adapted to different rhizobium species. These bacteria can survive for many years in the soil. However, when the legume has not been grown in a field for a long period, it may be necessary to re-introduce the bacterium by mixing it with the seed prior to planting. Examples of legumes are alfalfa, soybeans, snap beans, hairy vetch, peas, red, white and crimson clover, cowpea, sunn hemp, and fava bean. While direct transfer of nitrogen from the living legume to companion crop has been shown to be small, when part or all of the legumes dies, the proteins in their cells decompose, releasing nitrogen that can be absorbed by another crop. A hairy vetch cover crop can supply all the nitrogen needed by a following corn crop, while a crimson clover cover crop can supply roughly 80-100 pounds per acre of nitrogen-equivalent to the following crop.

Cover crops can be used for grazing, green chop, silage, or hay if needed.

Provide weed control. There is no practice that provides complete weed control – even herbicides provide weed control only for a short period of time, after which the growing crop provides weed control by out-competing them. Cover crops also provide weed control by competing with weeds when they grow. Some cover crops release chemicals that inhibit germination and early growth of certain weeds, and the mulch left behind supplies a physical barrier and light control mechanism that inhibits weed emergence.

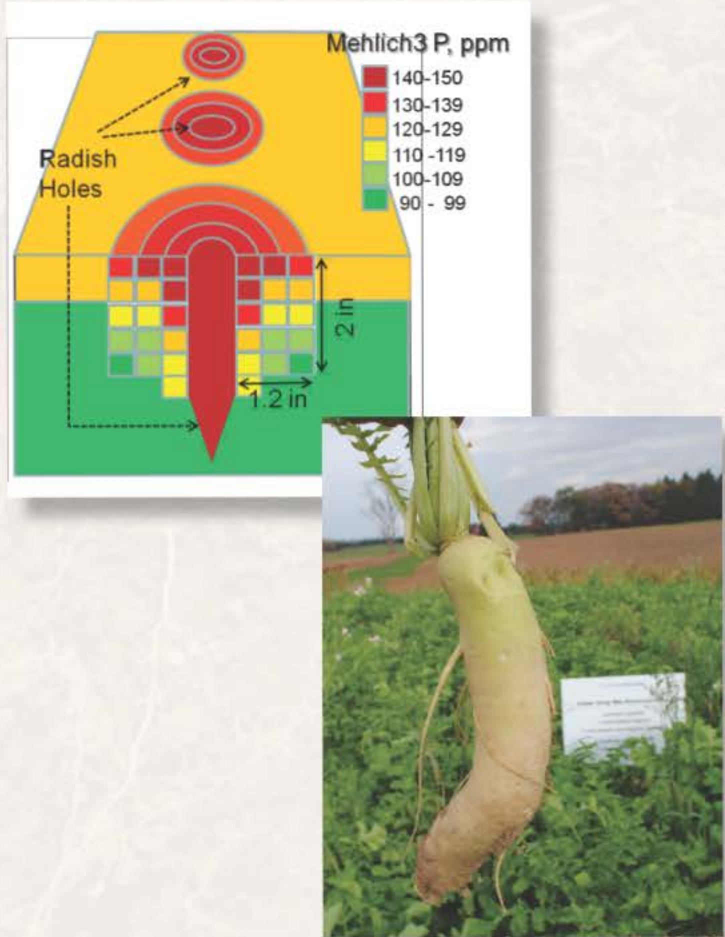

Figure 13. Available phosphorus was much higher in the vicinity of the holes of the decomposed taproots of forage radish in the spring. These cover crops can act like banded fertilizer by absorbing, retaining, and releasing phosphorus in available forms. *(From White and Weil, 2011).*

Provide forage. Although cover crops are not grown primarily for commercial purposes, they can be used for grazing, green chop, silage, or hay if needed. The use of cover crops for forage is beneficial because more feed is produced on the farm and fewer nutrients are imported in purchased feeds. This helps address the nutrient imbalance in Pennsylvania (nutrient importation in feed). Another important benefit of using cover crops for forage is that farmers are motivated to plant and manage the cover crops carefully to grow feed while providing environmental benefits at the same time. When cover crops are used for feed, it is recommended to leave a portion standing and provide enough time for regrowth to help feed soil microbes and provide soil armor.

3. Diversify Cover Crops

The third spoke is cover crop diversity. Mixing different cover crops and planting them together allows better use of water, light, and nutrients, often resulting in greater biomass production and better resource utilization *(Figure 14)*. Ecologists call this 'over-yielding.' This means plants compete less with plants from other species than with plants of the same species.

The different plant species use different resources, resulting in more efficient utilization. For example, plants with upright leaves catch a different spectrum of light than plants with horizontal leaves; legumes use atmospheric nitrogen while grasses and forbs use soil nitrogen; cool season grasses don't compete much with warm season grasses due to different temperature requirement, etc. The periodic table of cover crops can help you select cover crops with different characteristics when mixing species *(Table 1)*. Above and below-ground diversity also provides varied microbe food sources.

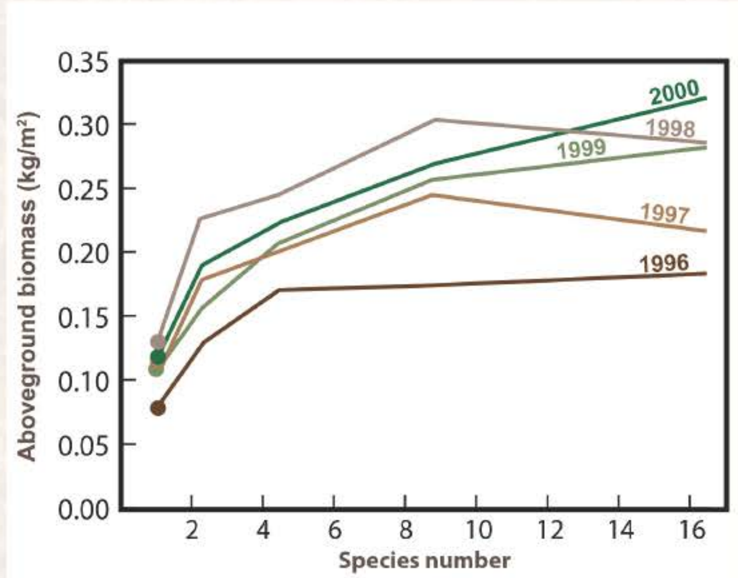

Figure 14. By increasing the number of species, the productivity of grassland plots increased. This is called 'overyielding' which means plants from the same species compete more with themselves than with plants from another species. By mixing cover crops greater benefits can be expected.

Table 1. Periodic table of cover crops showing cool season and warm season cover crops, grasses, broadleaves, and legumes to put together diverse cover crop mixtures.

Cover Crop Periodic Table

Cool Season Plants						Warm Season Plants		
Grass	Broadleaf Plants		Legumes					Grass
Barley								Pearl Millet (wk)
Oat (wk)	Arugula						Safflower (wk)	Foxtail Millet (wk)
Ryegrass	Flax (wk)						Buckwheat (wk)	Proso Millet (wk)
Wheat	Rape	Turnip (wk)	Winter Field Pea	Chickling vetch (wk)	Medic	Chickpea (wk)	Sunflower (wk)	Sudan grass (wk)
Cereal rye	Phacelia	Radish (wk)	Lentil	Red clover	Ladino clover	Cowpea (wk)	Amaranth (wk)	Teff (wk)
Triticale	Canola / Mustards	Beet	Spring Pea (wk)	Crimson clover	Bean (wk)	Soybean (wk)	Chicory	Grain Sorghum (wk)
Forage Oat (wk)	Ethiopian Cabbage	Tyfon (wk)	Vetch	Sweet clover	Alfalfa	Sun Hemp (wk)	Flower mix	Corn (wk)

(wk) = winter killed

(USDA NRCS)

4. Maximize Living Roots

The principle of maximizing living roots in soil year-round is the fourth spoke. Roots nourish microbes by providing a food source or by releasing nutritious compounds into the soil. It is estimated that plants release from 10-40 percent of the carbon fixed by photosynthesis through the roots. This carbon increases soil organic matter. Five different types of organic compounds released through roots are:

1. Cells are continually falling off root tips as roots grow;
2. Root tips produce an insoluble lubricating gel that helps the root penetrate small pores and provides the root tip protection against drying, helps gather nutrients, and binds soil particles together into aggregates that allow for better soil aeration and water percolation;
3. Soluble compounds called exudates are produced and leach from the root surface. These leacheates include organic acids, amino acids, proteins, sugars, phenolics, and other substances easily decomposed by microorganisms. The exudates have many functions; for example, they can solubilize plant nutrients such as phosphate from the soil particles, change the redox state on the root surface making iron more available, desorb nutrients from clay surfaces, or chelate zinc;
4. Sugars are fed directly by roots to fungi and bacteria that live in symbiosis with roots. Most well-known examples are rhizobia that fix atmospheric nitrogen in legume roots, and arbuscular mycorrhizal fungi that form bushy structures inside root cells connected to hyphae that extend the reach of the root into surrounding soil *(Figure 15)*.

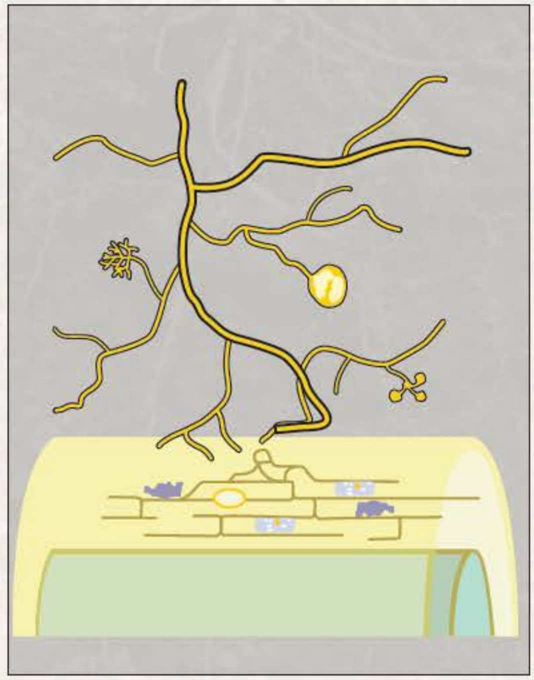

Figure 15. Schematic of the surface of a plant root with mycorrhizal fungi growing inside the root cells. Small bushy fungal structures called arbuscules grow inside root cortical cells. Water and nutrients are absorbed through the fine fungal hairs that extend into the soil and then passed on to the plant. Mycorrhizae release glomalin, an important glue that improves soil structure. (From mycorrhizaes.info/vam.html)

5. Dead cells are being lost from the root surface continuously as the roots develop. Subsequently, decomposer fungi and bacteria feed upon these dead cells located away from root tips.

The importance of living roots for soil structure improvement was evident in a Penn State study in which aggregate stability was measured at different times of the year in different crop rotations *(Figure 16)*. The study showed that aggregate stability increased during the period of active root growth and subsequently decreased when the root system declined. In the rotations with perennials, aggregate stability was always greater than in annual crop rotations due to prolonged presence of living roots.

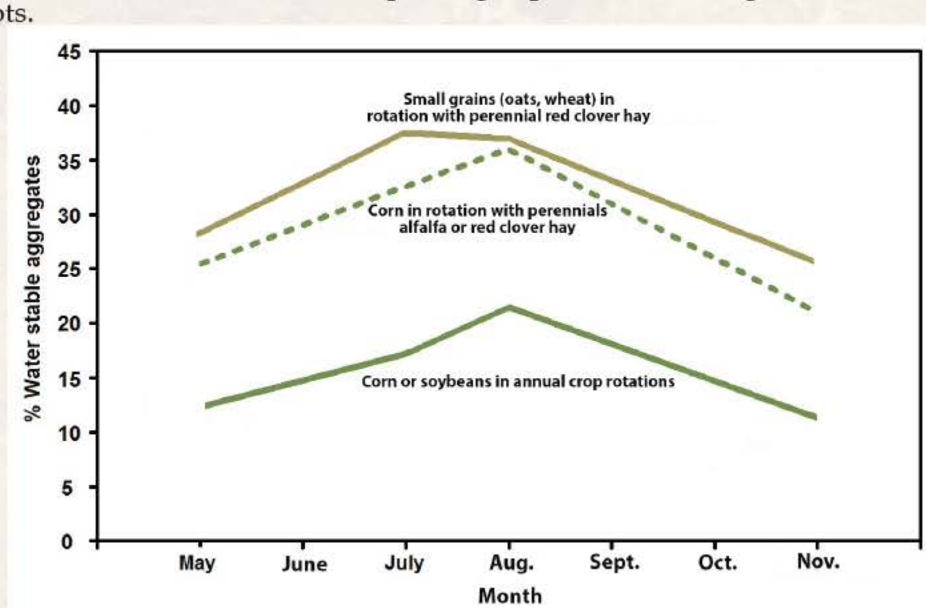

Figure 16. The dynamics of aggregate stability in a long-term crop rotation trial in central Pennsylvania. Aggregate stability increased with period of active root growth, peaked when root systems were at their top, and declined with root system decline. (*K. K. Grover. 2008. Long-term cropping systems effects on soil aggregate stability, corn grain yields, and yield stability. A dissertation in agronomy. The Pennsylvania State University, University Park, PA)*

5. Grow Living Plants

The fifth spoke is to have living plants in the field year-round. Living plants harvest sunlight and fix carbon dioxide from the air, producing different carbohydrates, and release oxygen. These carbohydrates include sugars, cellulose, hemicellulose, lignin, and many more. The carbohydrates are used to make plant cells and tissue. Because plants stand at the foundation of the soil food web, providing the energy source for most living organisms that cannot capture sun light, it is beneficial to have them growing in the field continually to keep the soil food web active *(Figure 17)*.

Cover crops are important because they keep living plants on the field during fallow periods. Cover crops should be planted as soon as the primary crop is harvested. Having a plan of how the cover crop will be established and the seed on hand prior to the planting window is very important. An exception to this may be when planting following small grain harvest because some cover crops, when planted too early, may be subject to winter kill. In this case it is justified to plant the cover crop a few weeks after small grain harvest.

It can be a challenge to plant cover crops early in the fall to produce enough growth to survive the winter and provide adequate cover. Cover crops should be selected that are adapted to fall and winter temperatures. Unfortunately, the harvest of summer crops such as corn or soybeans may be so late that cover crops produce little fall growth. Early-maturing corn hybrids and soybean varieties that can be harvested a week or two earlier than normal enable cover crops to produce better growth in the fall. Check variety trials to determine which short-season varieties can produce similar yields as long-season varieties in your geographic area.

Another opportunity for fall growth from a cover crop after corn grain or soybean harvest is to use interseeding (see next section). Late in the fall, a cover crop of rye or wheat can still be planted using 'dormant seeding.' Dormant seeding means that the seeds are in the soil but may not germinate or emerge until early spring. However, by planting time these cereals may be 6 to 12 inches tall. Dormant seedings are encouraged especially when some crop residues are present to help protect soil over the winter.

> *Living plants harvest sunlight and fix carbon dioxide from the air, producing different carbohydrates, and release oxygen.*

Manure may be applied on a dormant seeding in the spring. If a recommended fall deadline for cover crop planting is not met, dormant seeding still may be a good choice, although planting cover crops earlier for living cover in the winter is preferable.

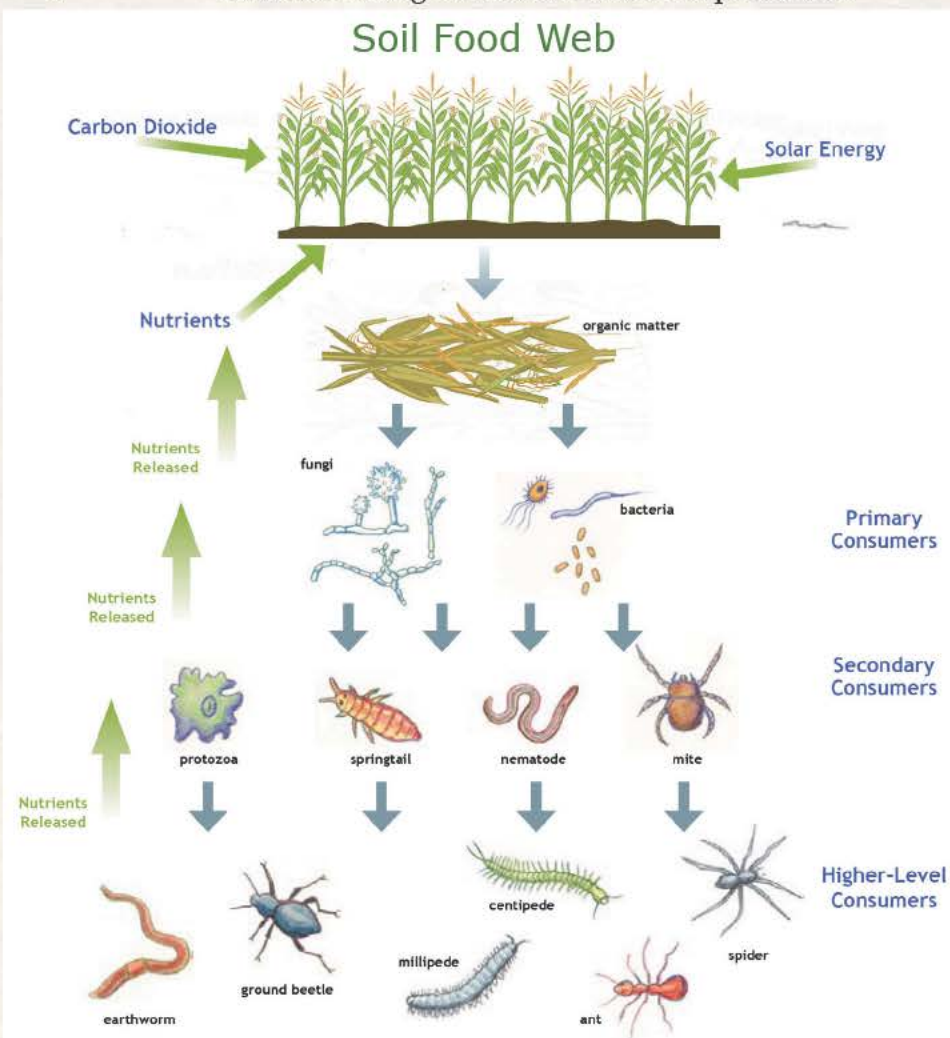

Figure 17. Plants stand at the beginning of the soil food web. Through photosynthesis they are able to capture the energy of sunlight and manufacture organic molecules that supply the energy for all other organisms. This dynamic system works best if living plants occupy the field year-long. *(Courtesy of www.landscapeforlife.org)*

6. Manage Carbon

The sixth spoke is carbon management. Carbon is not considered to be a plant nutrient and yet more than 40 percent of a plant is carbon (on a dry matter basis). Compare this with typical macronutrient contents of 1.5 percent nitrogen, 1 percent potassium, and 0.2 percent phosphorus. Farmers are really 'carbon managers'– they use plants to absorb carbon dioxide from the atmosphere and convert it into many different compounds, some of which are harvested *(Figure 18)*. A large portion of the carbon absorbed is used to feed soil organisms through the living roots. This carbon in the soil is of particular interest because it has such a profound effect on soil health.

A soil with high organic matter content is a good indicator of soil productivity. In the past this was called 'humus.' It is now recognized that humus is the highly stable form of carbon, and plants feed soil organisms with non-stable carbon compounds that are quickly consumed but contribute to the growth and activity of the entire soil food web. The below-ground part of the plant is probably more important than the above-ground part for increasing humus content. Therefore, it is important to have living roots in the soil year-round and return organic materials such as crop residues and manure to the soil. It is also important to limit soil disturbance because research has shown that large amounts of carbon dioxide are released when the soil is disturbed. The greater the volume of soil disturbed, the greater the carbon lost from the soil.

It is important to have living roots in the soil year-round and return organic materials such as crop residues and manure to the soil.

Maintaining a proper balance of carbon and nitrogen in the soil is very important in a healthy soil. As carbon is produced, a source of nitrogen needs to be available to provide the nutrients that microbes need to break down plant materials high in carbon, such as corn stalks or small grain straw. Rotations need to include legumes and soil organic matter content needs to be increased so that the soil has a larger source of nitrogen that can be made available when organisms and crops most need it. Using cover crop mixtures of both legumes and grasses is another way of providing microbes with both carbon and a nitrogen source to break down the carbohydrates and increase the level of organic matter in the soil.

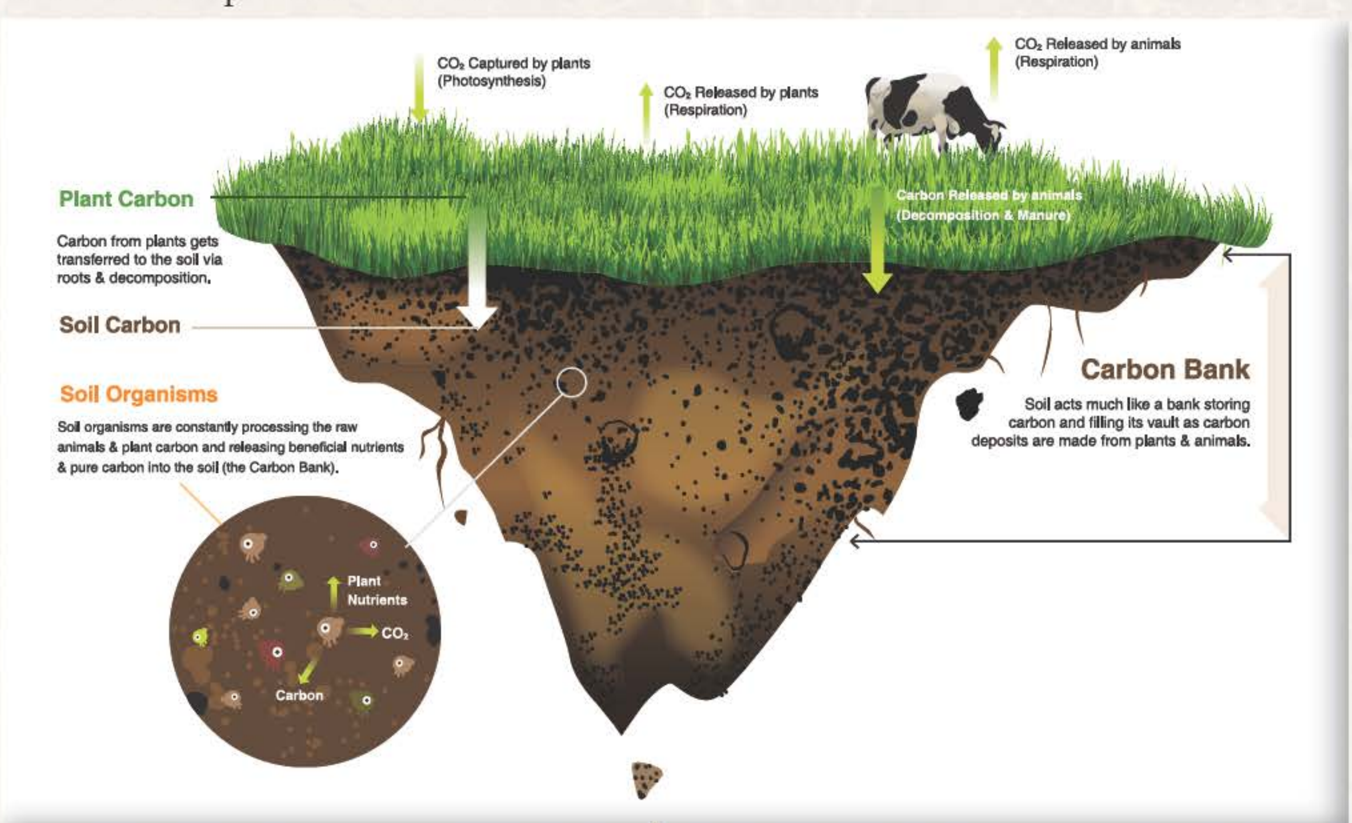

Figure 18. Managing carbon is key to soil health. *(From http://australiansoil.com.au/soil-management-benefits/)*

7. Use Interseeding

The seventh spoke is interseeding, sometimes referred to as 'relay cropping' – the establishment of a (cover) crop in a primary crop that is already growing. Examples of interseeding into annual crops are broadcast frost seeding red clover or yellow sweet clover in February/March into established winter wheat or barley. The practice of frost seeding has been quite successful because freeze-thaw cycles create some honey-combing of the soil surface which improves seed-to-soil contact. Seed predators are not yet very active and there usually is moisture at the soil surface to guarantee germination and early growth of the cover crop. The cover crop rarely compromises the yield of the main crop except that it may sometimes interfere with straw harvesting if the cover crop grows tall. The larger challenge is the competition of the main crop with the cover crop, which may cause the cover crop to struggle to establish. In most cases, however, there is a stand of clover visible after the small grain harvest that can be grazed, harvested, or terminated the following spring.

Broadcasting cover crops into summer crops is usually done in mid-June. This practice is relevant in corn for grain or soybeans because their harvest is late in the season for cover crop establishment. If a cover crop can be established prior to harvest it will be very beneficial. A high-boy type seeder which drops seeds between the rows can be used, or seeds can be broadcast using airplane or helicopter in corn or soybeans. These practices have not been as successful as frost seeding for the following reasons: (1) herbicide residues; (2) lack of honeycombing; (3) seed predation; and (4) lack of moisture for germination and early growth. Interseeders have been developed to overcome these challenges.

One unique interseeder can establish cover crops between rows of corn or soybeans planted on 30-inch spacing in no-till soils *(Figure 19)*. This interseeder guarantees good distribution of the seed which allows for lower seeding rates than in broadcasting, good seed-to-soil contact is achieved by using double disk openers, and there is greater protection of the seed from predators. Herbicide residues can still be a problem. Guidance on corn herbicides that can be used without hurting the cover crop is published in the Penn State Agronomy Guide Cover Crop Chapter.

Interseeding can also be practiced in perennial forages. Since most above-ground biomass of forage crops is removed it is common for forage fields to lack soil armor (cover) over winter. Such is the case with pure alfalfa stands. Planting a winter grain or other forage crop into the alfalfa in early to mid-August will provide soil armor, diversity, increased

Figure 19. Interseeding at 4-6-leaf stage (around the middle of June) enables establishment of cover crop if primary crop harvest is too late for cover crop establishment. New machinery has been developed that not only seeds the cover crop, but also applies side-dress nitrogen, and post-emergence herbicides, saving on operator time. *(Courtesy of Chris Houser)*

forage production, as well as possibly improved forage quality. In addition to winter grains, other cover crops such as oats, tillage radish, and some other small seeded cover crops can also be planted into alfalfa. There are many cover crops that make excellent forage, especially in mixtures. More diversity for soil microbes improves soil health. When planting into recently harvested forage crops, there is little above-ground biomass and planter adjustment and the planting process should not be difficult.

8. Plant Green

The eighth spoke is planting green. This practice refers to no-till planting primary crops into actively growing cover crops. This practice can be used when planting a crop such as corn or soybeans into a cover crop. It contrasts with planting into a cover crop that was killed one or two weeks before planting. Research has shown that by planting green, cover crop biomass can easily be doubled because cover crop growth is at its peak. Some important potential benefits of this practice include:

Research has shown that by planting green, cover crop biomass can easily be doubled because cover crop growth is at its peak.

- **Greater above- and below-ground cover crop biomass.** This helps to increase water infiltration and reduce surface runoff and soil erosion.
- **Legume covers will fix more atmospheric nitrogen** when growing an extra week or two.
- **The cover crop scavenges more nutrients** that might otherwise be lost by leaching to groundwater.
- **The cover crop will take up soil moisture** and help the soil to dry out and warm up quicker in periods of excess soil moisture.
- **The cover crops will harvest more solar energy and increase total soil carbon** important to increase the soil's water-holding capacity and nutrient pool.
- **The living cover crop root system produces easily digestible organic compounds** that feed living soil organisms in the rhizosphere (the zone close to roots). These organisms play important roles in building soil structure and nutrient recycling.
- **Hairpinning problems** of cover crop residue being pushed into the seed slot **should be eliminated or greatly reduced** because of better cutting of the green standing cover crop than that of dying crop residue that has been sprayed with herbicide but is not yet crisp and dry.
- **Potentially fewer problems with slug and cutworm pests** that move to the seedlings of the main crop when the cover crop is dead.
- **Potentially less soil or residue-borne disease** because of reduced splash from previous crop residue and soil onto the young seedlings of the primary crop.
- **Greater amounts of mulch in the crop** reduce weed pressure and result in cooler mid-summer soil temperatures.

Planting green is a new practice that is still under evaluation. Both the planter and attachments need to be in good condition and down pressure properly adjusted. It is important to account for thickness of standing or rolled plant cover when planting green. Down pressure on closing wheels needs to be set properly and seed openers need to be in good condition. Some farmers reduce the seeding rate of the cover crop so it is easier to plant in the spring. Shading of the primary crop seedlings by a tall cover crop can be undesirable, especially with corn. Cover crop rollers are available to mount on planters that flatten the cover crop onto the soil surface and part the cover crop so the double disk openers have less plant material to cut *(Figure 20, page 18)*.

Soil fertility needs to be optimized when planting green in a cover crop that has a lot of carbon in relationship to nitrogen. In this case, microbes may absorb nitrogen from the soil to decompose the cover crop residue and may cause a nitrogen shortage for the primary crop. This can be addressed by applying extra manure or nitrogen fertilizer, preferably placed close to the new seedling. Pest and disease benefits of planting green need more research, although preliminary results look promising.

Figure 20. A cover crop roller/row cleaner system designed by a Pennsylvania farmer/engineer from Perry County. It can be attached to a corn planter. It parts the cover crop in front of the double disk. *(Courtesy of Sjoerd Duiker)*

9. Enhance Soil Armor

The ninth spoke is soil armor. It may be broken down into two separate categories *(Figure 21)*. First is passive armor; this is the dead plant residue that remains on the soil surface following crop harvest or crop termination. Second is active armor; typically represented by an actively growing economic or cover crop.

Maximizing soil armor will weatherize cropping systems against the effects of drought, excess rainfall, and extremes in temperature. Maximizing soil armor is accomplished by leaving all crop residue remaining after grain harvest. The residue needs to be either left standing or be spread evenly over the surface of the field for success. If residue is clumped or concentrated in swaths, it will compromise establishment of the following crop, create non-uniform soil temperature and moisture conditions, and provide non-uniformity in food sources for biological life.

It is best to leave as much residue standing as possible during harvest so that there will not be a thick blanket of loose residue through which to plant. When residue is left standing, the soil warms up quicker in the spring and dries out faster than if the residue remained on the soil surface as mulch. The standing residue will be anchored in the soil, which facilitates planting of the next crop. Eventually, the dead stalks will fall and decompose on the soil surface. In situations where crop residues must be removed to meet the operation's objectives, it is essential to plant cover crops in a timely manner to compensate for the removed residue. Individuals who provide the best overall soil armor have learned how to combine both passive and active armor.

Some no-tillers experience problems with heavy residues, especially corn stalks. Issues include wet soils that delay spring planting and difficulty achieving adequate seed placement and slot closure. Some techniques to manage heavy corn stalks include:

- Let corn stalks stand after harvest.
- Apply manure to help soil microbes speed up residue decomposition.
- Plant cover crops into the residue; the drill cuts up the crop residue in smaller pieces and the increased biological activity and microclimate created by the cover crop favors residue decomposition.
- Use planter attachments to move residue from the row.

Figure 21. Soil armor includes passive armor, which is the crop residue from the previous crop, and active armor, which is the living cover crop. Both provide food sources for soil biological organisms and 'weatherize' your cropping system. *(Courtesy of Sjoerd Duiker)*

Irrespective of the management, having a healthy biologically active soil is key to the breakdown of residues, especially those with a high carbon to nitrogen (C:N) ratio and high lignin content *(Table 2)*. Fungi specialize in breaking down lignin so high-fungal populations found in long-term no-till soils will be beneficial. Long-term no-till is beneficial for earthworms that assist in the breakdown of crop residues. A readily available source of nitrogen to complete decomposition is important. A soil with high organic matter content will have more nitrogen available for microbes to decompose high C:N residue.

Table 2. Typical C:N ratios of organic materials

Material	C:N ratio
Soil bacteria	5
Actinomycetes	6
Soil Fungi	10
Hairy vetch cover crop	11
Alfalfa, young	13
Finished compost	15
Rotted manure	20
Alfalfa, mature	25
Rye, vegetative	26
Rye at flowering	37
Corn stover	57
Small grain straw	80
Hardwood sawdust	400

N.C. Brady and R.R. Weil. 1999. The nature and properties of soils, 12th Ed. Prentice-Hall, Upper Saddle River, NJ, USA.

On the other hand, residues higher in nitrogen, for example those from legume crops like soybeans, break down rapidly and leave very low levels of soil armor. Cover crops with higher C:N ratio should be used to improve soil armor. By knowing the carbon to nitrogen ratio of crop residues and cover crops it is possible to maintain adequate and manageable levels of soil armor.

Fifty percent soil armor is considered acceptable, but higher levels provide more soil erosion protection, help conserve soil moisture and reduce soil temperature during the summer months, and help protect and feed soil organisms. This is very different from the older recommendations when 30 percent residue was considered adequate.

Managing soil armor in forage cropping systems is challenging since minimal amounts of residues remain after harvest. This is especially true in pure stands of legumes such as alfalfa. One way to address this is to grow perennial grass/alfalfa mixtures instead of pure alfalfa. If this is not desirable, it is possible to interseed annuals, such as small grains, into pure alfalfa in early to mid-August following a forage harvest. To add more diversity, other low-growing species may be added. This provides active soil armor, increases forage production, and usually improves forage quality as well. It is also a good practice to leave the last cutting of the year standing to feed the microbes and protect the soil. However, if the last cutting is to be removed, then interseeding a winter small grain in August following a harvest will assure that some additional growing cover will remain as soil armor during the winter months and into the early spring.

> **"Feed the soil and the soil will feed the plant."**
>
> *- Carlos Crovetto, no-till pioneer*

10. Manage Nutrients

The tenth spoke is nutrient management. Adequate soil fertility is important to manage soil health for optimal crop production and environmental protection. Both nutrient excesses and nutrient deficiencies can have a negative impact on soil microbes and in turn on plant health and crop yield. A deficiency in one nutrient causes imbalances and can significantly impact both plants and biological processes. More diverse cropping systems and diverse cover crops increase the availability of nutrients from the soil and must be accounted for when considering the purchase of additional plant nutrients. The impact of plant roots and soil biology on the availability of nutrients for plant growth is discussed in several other sections of this publication. Currently, scientists and others are still learning how to best evaluate the impact of plant roots and soil biology on plant nutrition. Carlos Crovetto, long-term no-till pioneer from Chile, emphasizes: "Feed the soil and the soil will feed the plant." When soil health is improved it may be possible to use less fertilizer than generalized recommendations. To adjust rates it will become increasingly important to use the services of a Certified Crop Advisor (CCA) to help effectively manage nutrients in crop and forage production.

While it has long been acknowledged that organic matter and soil biology are a source of nitrogen for agricultural crops, laboratories had difficulty measuring this nitrogen in quick, inexpensive tests. As a result, for the last 50 years, soil tests have only measured the inorganic forms of nitrogen (nitrate, nitrite, and ammonium) and nitrogen recommendations may be based on these measures or are simply estimated based on yield goal. New tests are being evaluated that give measures of soil biological activity and predict the available nitrogen from organic matter. One test measures the carbon dioxide (CO_2) respiration of soil microbes. The more microbes in the soil sample and the more food sources they have, the more CO_2 produced. The test is a critical component of another laboratory test called the Soil Health Tool. This test uses water and mild organic acids (like those produced by plant roots) to measure available carbon, nitrogen, and other nutrients. The combined result of the new tests and lab analysis will generate improved understanding of soil health effects on plant nutrition. By using soil health analysis farmers can measure their progress as they implement management practices to improve soil health.

11. Manage Manure

The eleventh spoke is manure management. Manure is a source of nutrients and organic matter and helps to feed soil microbes and increase soil organic matter content *(Table 3)*.

Solid, semi-solid, or slurry manure contains significant amounts of organic matter and is more beneficial to the soil than liquid manure. Some guidelines in managing manure to optimize its value and minimize any negative impacts to the environment include:

- Apply manure when temperatures are low to limit volatilization of ammonia.
- Apply manure when moderate precipitation is predicted so the urea infiltrates the soil instead of being volatilized.
- Use shallow disk injectors to reduce nitrogen losses and minimize odors.
- Always apply manure on a growing crop whether it be a forage or cover crop so nutrients are absorbed by the living plants.

Table 3. Effects of 11 years of annual solid dairy manure on soil properties

	Solid Manure Application Rate (Tons/Acre/Year)			
	None	10 Tons	20 Tons	30 Tons
Organic Matter	4.3	4.8	5.2	5.5
CEC (me/100 g)	15.8	17.0	17.8	18.9
pH	6.0	6.2	6.3	6.4
P (ppm)	6.0	7.0	14.0	17.0
K (ppm)	121.0	159.0	191.0	232.0
Total pore space (%)	44	45	47	50

Fred Magdoff and Harold van Es., 2000. Building better soils for better corps. Handbook Series 4. Sustainable Agriculture Network, Beltsville.

Since manure is not normally applied to a growing grain crop, it is best to apply it to the preceding cover crop or use it on forages. Increasing numbers of producers apply manure to perennial hay and cover crops and use purchased nitrogen on the grain crop (typically corn) that can be sidedressed at the time of high crop nutrient demand.

In order to use manure most efficiently, and to meet state regulations, soil tests, manure analyses, and other information relevant to producing crops with manure should become part of a manure management plan. It is important to follow this plan and document the application of manure by field. A Certified Crop Adviser can assist in managing manure and nutrients in general.

Another way to manage manure application on the land is to use a separator to separate manure into liquids and solids, which are subsequently applied separately. The liquid portion contains more urea and soaks in the soil quickly where it is protected from volatilization, whereas the solids containing more of the phosphorus can be applied on soils most lacking in phosphorus. Manure digesters generate energy from methane gas while they separate liquids and solids and improve the stability of manure nitrogen. When liquids are separated from solids, the liquids can be applied either by irrigation or by using a drag hose to speed up application and reduce the potential for soil compaction. Drag hoses have more applicability than once believed and can speed up manure application and reduce compaction when soils are too wet to carry the weight of manure trucks or spreaders.

12. Manage Pests

The twelfth spoke is Integrated Pest Management. Managing pests is a challenging part of continuous no-till systems. Crop diversity and soil health improvement increases the number of beneficial organisms and helps keep pests in check. Insecticides commonly used in crop and forage production can also harm populations of natural enemies. For example, it has been shown that seed-applied systemic insecticides can be taken up by slugs eating young seedlings without harming them, but the ground beetles that prey on these slugs are killed *(Figure 22)*. Another example is the use of broadcast insecticide sprays applied after planting that kill pests as well as many beneficial insects. It is important to use insecticides and seed treatments only when they are needed using economic threshold populations as indicators and not just for the sake of 'insurance' against potential problems. In the long term it is more economical and effective to build populations of beneficial insects who keep pest populations in check. A Certified Crop Advisor can offer guidance with pest management. Ensure that the advisor you select is one who is familiar with methods of building soil health and working with nature to manage pests. By using methods of integrated pest management, soil health in continuous no-till is improved, making cropping systems more profitable.

13. Avoid Compaction

The thirteenth spoke is to avoid soil compaction. One of the great benefits of using continuous no-till is that the soil supports weight better and is less sensitive to compaction. This is due to high organic matter content near the soil surface, high microbial and earthworm activity, and a firm soil matrix that is perforated by biopores for water infiltration and percolation, gaseous exchange, and habitat provision for soil organisms and roots.

However, once compaction is caused the no-tiller may experience its aftermath for several years. It is important to understand what causes compaction and to avoid it as much as possible. Soil compaction is primarily of concern when the soil is wet. Soil moisture acts as the lubricant that allows soil particles to slide over each other and be packed to higher density. Continuous no-till soil is beneficial because the soil drains excess water more readily than tilled soil that lacks continuous macropores, but it is important to stay off soil that is too wet.

Figure 22. Pesticide applications can have unintended consequences. They can kill insects such as these firefly larvae that are a predator of slugs, while leaving the slug unaffected. Pesticides should therefore only be applied when needed, using crop scouting and economic thresholds. *(http://backyardsfornature.org/wp-content/uploads/2013/07/firefly_eats_slug-image-by-Phillip-SITNAM7-in-Climax-Michigan.jpg)*

Shallow compaction is caused by the pressure exerted on the soil surface. The weight and footprint of equipment or animals determine how much surface compaction is caused. Tire inflation pressure is important – the lower the tire pressure, the larger the footprint and less the opportunity for compaction. Equipment using tracks increase footprint and therefore reduce surface pressure too. Massive, living root systems in the soil help the soil resist compaction and bounce back from its causation. Fibrous cover crop root systems are effective to achieve reduced compaction.

Shallow compaction or tightness near the soil surface can be associated with the transition to continuous no-till without cover crops and soil armor and can cause increased soil erosion due to increased surface runoff. Even in long-term no-till, without soil armor or crop canopy or both, soils can become tight near the soil surface and lose their ability to infiltrate rainfall. This happens when the soil surface is not protected from the pounding of raindrops, especially during intense storms. It is therefore important to provide continuous cover but also to make use of different root systems. Besides the fibrous root systems tap root systems are beneficial to create macropores and maintain soil porosity. Forage radishes, turnips, red clover, alfalfa, and sunflower are examples of (cover) crops with taproots.

Soil compaction at intermediate depth (two- to four- inches deep) may be a problem in no-till. Compaction by heavy equipment may cause platy soil structure at this depth. This layer is more sensitive to compaction than the surface because its organic matter content is not as high, root density is lower, and the soil moisture content is high many days of the year due to the conservation of moisture by crop residue. Compaction of this layer may easily become a problem where farmers do not make use of living cover year-round. The living root system reduces moisture content and acts as a 'geotextile' that makes soil resist compaction and reduces platy soil structure. Compaction at intermediate depths can also be the remnant of tillage with a disk or vertical tillage tool that was operated at the same depth year after year when soil moisture content was too high resulting in massive soil structure.

Some Pennsylvania farmers can triple crop yield in one year by integrating crops and animals.

Deep compaction can be associated with prior plow pans or the use of heavy equipment when soil moisture content is too high. When evaluating soil compaction the first step is to check the soil type to see if that soil mapping unit naturally has a restrictive feature such as a fragipan. Natural compaction is difficult to remedy but can be somewhat alleviated by using cover crops and primary crops with deep roots that can penetrate these layers. Deep burrowing animals such as earthworms help alleviate deep compaction and are enhanced by the soil health practices in this publication.

Soil damage by prior tillage resulting in compaction is not easily alleviated. Using a subsoiler may be called for if soil compaction is very serious. It is important to use a subsoiler that does not invert the soil but fractures it. Unless subsoiling is done when the soil is dry, the impact will be minimal and sometimes causes new compaction. Normally, the only time the soil is dry enough to consider subsoiling is in mid-summer or in early fall, following harvest of a crop such as a small grain. In a corn-soybean rotation, there are limited periods of time when the soil moisture content is optimal for successful subsoiling. It is better to avoid tillage and rely on nature to alleviate compaction.

14. Integrate Crops and Livestock

The fourteenth spoke is crop and livestock integration. The trend in agriculture has been to separate crop and livestock production. Farmers who include animals as part of the farm operation are more likely to adopt cover crops for manure and compaction management, and as a possible feed for ruminant animals *(Figure 23)*. Further, manure from ruminant animals is a great soil amendment to improve soil health in cropland. More intensive crop rotations are possible with livestock on the farm because crops can be grazed or harvested early for green chop, silage, or hay. Some Pennsylvania farmers can triple crop yield in one year by integrating crops and animals. Crop diversity tends to be greater on animal farms because of the nutritional needs of the animals. However, the animal and crop enterprises are usually separated, even if present on the same farm.

Farmers from different parts of the world, including some innovators in Pennsylvania, have shown that integrating grazing ruminant livestock and crop production can have advantages:

- **Increased profits** due to reduced costs and increased revenue. For example, grazing animals on crop residue and cover crops results in a new income stream and better land utilization.

Figure 23. Reintegrating livestock with crop production can contribute to improved soil health in continuous no-till systems. *(Alan Franzluebbers)*

- **Reduced risk** through diversification of enterprises. The farm becomes less sensitive to price fluctuations in one commodity and to weather variability because crops are not all grown at the same time of the year.
- **Easier pasture renovation** after annual crops. By rotating to an annual (cover) crop it is possible to completely eradicate the old unproductive stand so that a clean, improved perennial pasture can be established.
- **Increased whole herd-carrying capacity** for graziers. Some perennial forages produce little during the summer heat. By including summer crops or summer annual forage mixes such as sorghum, sudangrass, or their hybrids, grazing corn, sunflower, sunn hemp, cowpea, forage soybeans, buckwheat, and others, the farmer will have higher productivity. Some winter annuals start growth early in the spring, providing pasture at a time when perennial forages are not yet productive.
- **Decreased fertilizer needs** due to the effective use of manure and urine in intensive grazing operations and integration of legumes in the crop rotations.
- **Decreased crop disease, weed and pest pressure** through the increased diversity.
- **Improved soil health** because of the rotations of annuals and perennials, grasses, legumes, and forbs; the manuring, urinating, and salivating of the animals; and trampling of part of the crop residue into the soil when ultra-high density grazing is used. The diversity of root systems and symbiotic relationships of crops, bacteria, and fungi stimulate soil microbial activity and aggregate stability.

Additional Best Management Practices for Erosion Control

While improved soil health can alleviate most erosion issues, there can still be some problems of concentrated surface water flow. One common scenario is where springs or seeps exit the hillside or where runoff from another area flows into a field. In these situations, producers may need to utilize grassed waterways and structural practices to manage concentrated flow. These practices may also be needed in larger drainage areas with potential concentrated flow erosion within cropland areas. Some no-tillers address areas that have been gullied by filling them with appropriately sized rock and field stones to stabilize the area and retain the ability for some water to flow through the stones. Another scenario is when the soil is frozen and begins to thaw at the surface. Snow melt or heavy rainfall at this time can be devastating since infiltration is almost zero, no matter how healthy the soil, resulting in near 100 percent runoff. This is where living cover and heavy residues may need to be coupled with surface water management practices. In continuous no-till, concentrated flow erosion is not hidden as it is where gullies can be covered up by tillage every year. In continuous no-till, visible erosion can be the culmination of a number of years. It may be for this reason that some individuals have associated no-till planting with soil erosion. In reality, however, soil erosion with tillage is much higher but rills and small gullies are covered up every year. Nonetheless, if there are problems with concentrated flow erosion they need to be addressed quickly to avoid gully formation in continuous no-till.

Conclusion

This publication emphasizes the natural principles of the no-till system. Soil health is like the hub of a wheel and continuous no-till is the rim. When all 14 spokes connecting hub and rim are present, the system is highly productive, profitable, and environmentally sustainable.

Remember...
No-till works best when all the spokes are addressed!

Soil health and continuous no-till systems are closely connected. Soil biology is the core of the continuous no-till production system. The 14 principles will reduce pesticide and chemical fertilizer use, reduce soil erosion, and increase organic matter so that the focus will become building soils instead of trying to minimize their degradation. The management techniques described in this publication such as soil armor, cover cropping, and maximizing the amount of time a growing crop is present on the land over the entire year, will reduce sheet and rill erosion to much less than T (tolerable soil loss as defined by NRCS) and concentrated flow erosion will be minimized because of high infiltration.

The new system is more management intensive, as there is an increased need for planning and keeping abreast of the latest research to accomplish the promise of improved soil health. It is necessary to plan a crop rotation and evaluate cover crop mixtures, order seed in advance of the main crop harvest, keep planting equipment in working order, and plant cover crops immediately after harvest. Because soil health and managing for biology is still a new concept, it is important to keep up-to-date with new research. There are many opportunities to learn about new technologies and ideas at meetings, conferences, field days, on websites, and in farmer groups. Some educational opportunities available in Pennsylvania are identified at the end of this publication.

Figure 24. By using the 14 spokes with continuous no-till, soil health can be dramatically improved. *(Courtesy of Sjoerd Duiker)*

Glossary of Terms

Aggregation – The process whereby sand, silt, and clay particles are bound together, usually by natural forces and substances derived from root exudates and microbial activity.

Concentrated flow erosion – Refers to rill and gully erosion.

Continuous no-till – The planting of all crops in the rotation without the use of any prior tillage. The no-till planter or drill accurately places the desired crop seed at the proper depth while providing good seed-to-soil contact. Planters and drills may or may not use coulters. They may be equipped with disk fertilizer openers to properly place plant nutrients. Shallow disk injection of manure or fertilizer is also considered to be consistent with continuous no-till planting.

Crop residue – Dead plant material from previous crops. In no-till crop residue is left at the soil surface. Also called 'passive armor.'

Exudates – Low molecular weight organic substances that enter the soil from plant roots.

Gully erosion – The removal of soil through the cutting of few large channels where runoff concentrates. Cannot be easily obliterated by tillage and obstructs movement of farm equipment.

Hairpinning – Pushing crop residue into the seed slot and planting the seed on top, resulting in poor seed-to-soil contact.

Intercropping – A form of polyculture where several crops are grown in a field at the same time in alternating rows.

Infiltration – The entry of water into the soil.

Interseeding – Planting or drilling a crop or cover crop into an already established crop.

Macro pores - Large pores responsible for rapid percolation of water into and through the soil profile.

Micro pores – Small pores holding water for plant roots to extract as well as water that is unavailable to roots in the smallest pores.

Percolation – Downward movement of water through soil.

Polycultures – Growing multiple crops or cover crops in the same space at the same time; also called mixtures.

Rill erosion – The removal of soil through the cutting of many small, but conspicuous, parallel channels where runoff concentrates. The channels are usually less than four inches deep and can be crossed easily by farm equipment.

Rotational tillage – Alternating tillage and no-tillage for the establishment of subsequent crops.

RUSLE - Revised Universal Soil Loss Equation used to predict erosion by USDA-NRCS

Rhizosphere – The narrow region of the soil around roots that is influenced by root excretions and associated microbes.

Sheet erosion – The more or less uniform removal of soil from an area without the development of conspicuous water channels.

Soil loss tolerance (T) – Denotes the maximum rate of soil erosion in tons per acre per year that can occur and still permit crop productivity to be sustained economically as determined by soil scientists. It typically ranges from 1-5 T/A/yr., depending on soil type.

Vertical tillage – Tillage that does fracture but does not invert the soil or move it laterally as occurs when concave blades are used. Vertical tillage tools have flat blades (not curved) as opposed to concave blades similar to those on disks.

Educational Opportunities

Success with continuous no-till systems is knowledge intensive. New information is coming out continuously and it is very important to keep up-to-date with new developments in the field and implement changes to improve the system on your farm *(Figure 25)*. Here are a few educational opportunities available to farmers, crop consultants, agri-business personnel, educators, and researchers.

Meetings, conferences, and field days

Conferences and field days held outside Pennsylvania:

The National No-Till Conference. This conference is organized by No-Till Farmer, an organization primarily active in the Mid-West. It is held in different locations every year in January. Additional information: *www.no-tillfarmer.com/nntc*

No-Till on the Plains winter conference and Agriculture's Innovative Minds Symposium. This conference is organized by No-Till on the Plains and is focused on farmers in the Plains regions of the U.S. and Canada. It is held in a location in the Great Plains, usually in January. Additional information: *www.notill.org/events/*

Conservation Tillage and Technology Conference. This conference is organized by The Ohio State University, Conservation Districts, USDA-NRCS, USDA Farm Service Agency, and The Ohio No-Till Council. It is usually held in March in Ada, northwestern Ohio and geared to Ohio agriculture. Additional information: *fabe.osu.edu/CTCon*

Cover Crop Tours at Big Flats Plant Material Center in New York. Many different cover crops are tested every year at this center which can be visited at open days which usually also include a conference with renown no-till and soil health speakers. Additional information: *www.nrcs.usda.gov/wps/portal/nrcs/main/plantmaterials/pmc/northeast/nypmc/*

Figure 25. Success with no-till is knowledge intensive. Farmer organizations such as The Pennsylvania No-Till Alliance, Conservation Districts, Penn State Cooperative Extension, and USDA-NRCS organize many field days to promote the successful application of no-till through shared ideas and experiences.

Conferences and field days in Pennsylvania:

Southwest PA Regional No-Till Conference. This conference is organized by a group of Conservation District, RC&D Council, NRCS, Penn State Cooperative Extension, and agribusinesses and is usually held in January in Latrobe. For more information contact Westmoreland Conservation District at (724) 837-5271.

Cover Crop Solutions Fall Field Day. This field day is organized by Cover Crop Solutions at Cedar Meadows Farm in Holtwood, Lancaster County. It is usually held in October or November. Additional information: *www.covercropsolutions.com/events/*

There are many other conferences and field days held in Pennsylvania organized on an ad-hoc basis by the Pennsylvania No-Till Alliance, USDA NRCS, County Conservation Districts, Penn State Cooperative Extension, Agricultural Suppliers, and others. The best contact for more information is your local Penn State Cooperative Extension Office and the Pennsylvania No-Till Alliance web site - *www.panotill.org*.

Web sites and other media sources

USDA-NRCS Soil Health Campaign:

www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health

No-Till Farmer: *www.no-tillfarmer.com*

No-Till on the Plains: *www.notill.org*

Pennsylvania No-Till Alliance: *www.panotill.org*

Penn State Cooperative Extension: *www.extension.psu.edu/plants/crops/soil-management*

Farmer-to-Farmer Networking:

Members of the PA No-Till Alliance and affiliates/ Sponsors of the PA No-Till Alliance. Their contact information may be found at *www.panotill.org*.

Soil Health Champions are producers who are successfully implementing advanced systems of continuous no-till, cover cropping, and improved soil health. Their contact information may be found at *http://notillsoil.org*.

A note on sorting through no-till articles, research, and other published information:

A wealth of information is available today, from the internet to farm publications and the research sector. This availability is a good thing, but it is common to hear or read conflicting information. It is up to the reader to sort through these apparent conflicts and decide what information is most pertinent for their own crop production system. Some rules of thumb to help interpret information might include:

- Seek out information from local sources, folks you know and can talk to.
- Look for information from an independent or other well qualified and experienced source. Today, some crop scouts specialize in helping producers with continuous no-till.
- Attend field days where you can see farmers implement or test the practices. On-farm research, especially in your locality, may be the most appropriate source of sound information.

With reference to information coming from university and on-farm research about continuous no-till planting:

- Were yield data and other relevant results taken from land that has been no-tilled for at least three years?
- Were management techniques to improve soil health a part of this system?
- Was planting equipment adjusted, maintained, and equipped with attachments needed to plant under continuous no-till conditions?
- Were the timing of planting and management appropriate for continuous no-till systems?

Some research studies do not pass the testof the four items listed above. Therefore, many successful continuous no-till producers evaluate published research by doing on-farm research or by splitting fields and trying different management techniques on their own farm. By doing some of this on their own farm, and keeping in touch with others who do so, farmers can continue to improve their no-till system.