

Grasslands are King

-- when it comes to soil carbon sequestration. The fibrous roots of perennial grasses turn over rapidly in the soil, feeding soil microbes that help organic matter accumulate (1). The highly productive soils of the North American Midwest formed over tens of thousands of years under tallgrass prairie ecosystems populated by millions of grazing animals that moved frequently in dense herds. The deep rooted, diverse prairie plant community (Fig. 1) was especially well-suited to building soil carbon, but cool-season grasses and legumes in pastures can be managed for this purpose as well. What do we know about carbon storage in grasslands and how can we manage our pastures to encourage carbon sequestration?



What is carbon sequestration?

Through photosynthesis, plants capture the sun's energy and store it in chemical bonds when they combine carbon dioxide and water to form carbohydrates. In our pastures, grasses and legumes use this fuel for maintenance, reproduction, and growth. If we manage well, there is enough growth to feed our grazing livestock and leave some residual to feed soil microbes - largely fungi and bacteria - that break down plant tissue and recycle nutrients. It is this last pool of carbohydrates that may be converted to more stable forms of soil organic matter. For carbon to be sequestered, it must be in a form that won't be readily consumed and respired back to the atmosphere as carbon dioxide.

Knowledge of the plant-soil-microbial ecosystem is growing fast – yet there remain many questions to be answered. The picture that is emerging is that within the rhizosphere (the zone where plant roots and microbes interact), a complex web of mutually beneficial interactions occur and the health of that ecosystem leads to healthier outcomes for our pastures, livestock, and the nutritional value of their meat and milk.

Not all organic matter is created equal

Scientists describe two distinct pools of soil organic matter. Particulate organic matter (POM) is plant tissue that is resistant to decomposition by microbes because of low nitrogen content. But, while it is resistant to decay, POM is not as stable as the other organic carbon pool called mineralassociated organic matter (MAOM), which is comprised mostly of the dead bodies and metabolites of microbes. MAOM is higher in nitrogen and more persistent in the soil because it is chemically and physically bound to soil minerals, in particular, clay and silt. Glomalin and other glycoproteins are types of MAOM that hold soil aggregates together. Although it too can be drawn down in the soil under intensive cultivation. MAOM is the gold standard for soil carbon sequestration.

In recent years, some farmers have reported adopting practices that produce significant increases in soil organic matter. Much of this is POM, which is good while it lasts, but POM is susceptible to being returned to the atmosphere if water, nitrogen, and oxygen make decomposition rates (POM outputs) higher than rates of plant photosynthesis (POM inputs). We cannot be assured that this carbon is truly sequestered for the long term, but if the land remains under perennial cover and is not subject to tillage, much of this POM may persist or be converted to MAOM.

We might think of the soil microbial community (Fig. 2) as the 'financial manager' of soil fertility, water, and organic matter. POM is the liquid asset portion of the portfolio, like our checking account and short-term savings account. When conditions are right, resources may be converted from POM into MAOM, which might be viewed as the longterm investment account. As any good financial manager will do, soil microbes sometimes also break down MAOM for immediate use or trap some POM in soil aggregates for longer term savings, all to aid in maintaining or ideally increasing overall assets. Keeping the soil microbial community healthy gives it the tools to help keep our system resilient through all kinds of conditions and provide a consistent source of nutrients and water holding capacity. The key to carbon sequestration in the soil is keeping an effective balance of POM and MAOM for longterm storage (2, 3). Keeping the soil microbial community healthy with abundant and diverse plant litter inputs, shoots and roots, allows that to happen.

Figure 2. Source: European Commission, Joint Research Centre, European Soil Data Centre https://esdac.jrc.ec.europa.eu/ - Themes – Soil Biodiversity



In dynamic systems, carbon cycling and sequestration vary

There remain a lot of questions about what conditions promote soil carbon sequestration. The references listed at the end of this fact sheet summarize over 100 studies on soil carbon dynamics in grasslands and the results are still inconclusive. This is because, unlike in forest ecosystems where much of the carbon is stored in wood which is easily measurable and quite stable, carbon storage in grasslands is part of a dynamic system in constant flux. There is a great deal of carbon cycling between the air, plants, plant roots, soil microbes, and organic matter pools (POM and MAOM). For that reason, carbon storage in our pasture soils is influenced by many factors including ones that we have no control over such as soil texture, long-term climate and short-term weather conditions. There are also factors that we can control, including soil health, grazing management, and pasture species composition. Improving these factors provides many benefits in terms of pasture health and resilience, whether or not they result in increases in soil organic matter.

Soil texture and climate put bounds on what's possible

For any farm, the texture of the soil, its mineral makeup of sand, silt, and clay particles, is a given. We have to work with what we've got. The size of the soil particles, along with rainfall amount and timing, influence water and nutrient availability in the soil. Water and nutrient availability, along with seasonal temperatures, dictate the productivity of the plant community as well as the effectiveness of the microbial community in decomposing and recycling plant materials.

Like other biological communities, the soil microbial community has a set of conditions under which it functions most effectively. Those happen to be in loam soils that are characterized by a balance of small (clay), medium (silt) and large (sand) particles. The mix of particle sizes in loamy soils creates pore space providing oxygen and water holding capacity that allow a diversity of soil microbes to thrive. At the sandy end of that spectrum, the soil has adequate oxygen but can experience periods of low moisture that limit plant growth and microbial activity and thus slow the accumulation and breakdown of plant matter into soil organic matter by microbes. Sandy soils are also hindered by a lack of appropriate surfaces on sand grains for MAOM storage. At the clay end of the spectrum, lack of drainage usually means microbial activity is low, allowing plant matter to accumulate as POM even when plant growth is relatively low. Under extremely wet conditions such as in wetlands, significant POM can accumulate over time, but the soil environment may be too wet for microbial conversion of that material to MAOM.

Because of the inherent physical, chemical, and biological characteristics of soils, there are limits to how much stable organic matter can accumulate in a particular soil. Table 1 shows organic matter ranges for typical Midwestern agricultural soils (4, 5). Your soils may vary depending on previous management or soil sampling method. It's pretty easy to decrease soil organic matter below these levels with tillage or other poor management practices, but it is unlikely that you can permanently increase levels significantly above these ranges. Keep in mind that in a perennial pasture setting, a large amount of fresh undecomposed plant material and POM may accumulate at or near the soil surface, which is a good thing because it provides cover and habitat, but can bias soil organic matter estimates if included in soil sampling efforts.

Table 1. Range of organic matter found in agricultural soils of the upper Midwest (Schulte et al. 2005)

	Organic matter
Soil color & texture	(%)
Light and dark colored loamy	
sands	0.4 - 1.2
Light colored sandy loam	1.2 – 2.0
Dark colored loams	2.0 - 3.5
Light colored silt loams	2.0 - 3.5
Dark colored silt loams,	
loams, and clay loams	3.5 – 5.5
Imperfectly drained soils	5.5 – 9.0
Poorly drained soils	9.0 - 20.0
Peats & mucks	>20.0

Managing pastures to promote carbon sequestration

Because pasture is a perennial system, you can expect significant changes in the initial three to five years after establishment. Although accumulation of soil organic matter slows as the pasture matures and the plant and microbial communities recalibrate to a new steady state, soil organic matter and plant community vigor can continue to improve over decades when maintained under well-managed grazing. However, the changing climate makes the concept of a steady state or equilibrium less certain. You are likely to see the most change initially in the top foot of soil where cool-season grass roots concentrate. As a well-managed pasture matures, little additional organic matter will be broken down and stored in the more stable MAOM form at shallow depths; however, there is the potential to increase soil organic matter deeper in the soil profile through improved management.

Annual to perennial

One situation in which there is almost always a clear increase in soil organic carbon is when converting annually cropped soil to perennial pasture, especially when tillage was part of the annual system. In a meta-analysis of 93 studies, researchers found an average 39% increase in soil organic carbon when annual cropland was converted to perennial grassland (1). Several studies of implementation of management intensive grazing in the southeastern U.S. (6) and in Michigan (7) suggest significant increases in soil organic carbon over the first four to six years before leveling off at the top end of the ranges shown in Table 1.

Sandy and degraded soils

With adequate rainfall or irrigation, sandy and degraded soils with low organic matter are likely to see an increase in soil organic matter over time when converted to well-managed pasture. In sandy soils, organic carbon storage may be negative or positive at low rainfall levels of eight to 16 inches, but researchers found that carbon sequestration was likely to occur when rainfall or irrigation was at or above the 30" per year range (8). Increasing soil organic matter in sandy or degraded soils can create a positive feedback loop, as increased organic matter allows the soil to hold more moisture, which may increase plant productivity, providing more food for microbial activity, resulting in more organic matter deposition (9).

Improving soil health

Practices that improve soil health can encourage both pasture productivity and enhanced decomposition of plant tissues to POM, leading to improved soil structure and sequestration of carbon in the form of MAOM. As a livestock grazier, it is relatively easy to practice the five soil health principles compared to crop farmers with no livestock.

The principles are:

- Armor the soil with continuous living cover;
- Minimize soil disturbance by reducing or eliminating tillage and increasing use of perennial pasture;
- Increase plant diversity within a field with complex pasture mixtures;
- Keep living roots in the soil year round;
- Integrate livestock into cropping systems.

For more information on soil health visit the Natural Resources Conservation Service at https://www.nrcs.usda.gov/wps/portal/nrcs/main /national/soils/health/

Grazing management

The principles of management-intensive grazing include rotating the herd or flock from paddock to paddock, leaving enough residual to spur regrowth, and allowing for sufficient rest and recovery of the plants before the next grazing event. By following these three practices, a dense, tall sward is achieved that increases livestock intake (10). Management-intensive grazing not only increases production, quality, and dry matter intake of the pasture (11), but also can result in net carbon uptake and possibly sequestration (12). If we graze too hard or have inadequate forage recovery periods, we leave little or nothing for the soil microbial community, and we are not likely to gain soil organic matter. Leaving significant and diverse residual plant biomass, while using practices that encourage root growth and deeper rooting depth, are the best approaches we have to promote carbon sequestration (13).

Increasing rooting depth

Compared to leaves and stems, plant roots are a source of plant tissues that is directly available to soil microbes to be broken down and stored or recycled. Plant roots also exude soluble carbon compounds that can directly feed soil microbes and encourage colonization of the rhizosphere by friendly bacteria and fungi that extend the reach of the plant roots in exchange for those carbohydrates. The majority of grass roots, especially among cool-season grass species, are concentrated in the top foot or so of the soil. As that layer of the soil becomes 'saturated' with organic matter, encouraging deeper rooting depths can push those grass roots down into the soil profile, allowing for potential increases in organic matter at greater depths (14). Managing for longer rest periods, and the occasional use of high stock density grazing (mob grazing), can encourage roots to grow deeper into the soil profile.

Think about pasture aboveground growth as a reflection of rooting depth. If you always turn your livestock into a pasture at six or eight inches and graze down to two inches, grass roots are more likely to be concentrated in the top six to eight inches of the soil profile. Waiting to graze until the sward is 12 or more inches and leaving four to six inches of residual will give the plants time to accumulate greater root reserves and allow roots to penetrate farther into the soil profile. Increasing root volume and rooting depth will not only encourage organic matter accumulation as those roots decompose, but as the plant roots extend and organic matter is formed deeper in the soil profile, soil water holding capacity increases and the plant is able to scavenge nutrients and moisture from a larger volume of soil.

Pasture species composition

Legumes and improved grass varieties

Several short-term studies (summarized in reference 1) indicate that incorporating legumes into perennial pastures can result in significant increases of soil carbon. Likewise, incorporating improved grass varieties into low-productivity grasslands increased soil carbon during the first two to three years of the studies (1). Over time, soil organic matter will reach a new, higher equilibrium when the soil reaches its capacity to store carbon.

Pasture plant diversity and rooting depth

Increasing pasture species diversity in managed rotational grazing systems can have many benefits, including greater and more consistent productivity and forage quality (15). As the pasture matures and soil organic matter in the top foot stabilizes, pasture species diversity can enhance rooting depth and lead to organic matter deposition deeper into the soil profile. Diverse plant species composition also is likely to lead to a more diverse soil microbial community and improved soil health. In a comparison of twospecies and five-species cool season pasture mixes, researchers found that rooting depth and volume of roots were greater in the more diverse mix, resulting in more than three times as much soil organic carbon throughout the three-foot soil profile (Fig. 3) (16). In a second study, a four-fold increase in root biomass was observed at the two and three-foot levels under an 11 species pasture



mix compared to a two species mix (15). Both studies were conducted under a dairy rotation with moves to fresh pasture after each milking. When establishing a new pasture, consider planting a complex mixture of at least five species, preferably more, including the three plant functional groups: grasses, legumes like clover or alfalfa, and broadleaves such as chicory or plantain. Non-invasive broadleaf weeds like dandelion or curly dock can enhance pasture diversity as well, as long as they are palatable and are readily grazed by your livestock. In existing pastures, avoiding herbicides for weed control and interseeding legumes and broadleaves can increase diversity. However in a well-established cool-season pasture, introducing additional grass species is challenging without suppressing existing grass plants. Plant species diversity can also be increased using adaptive high stock density grazing management creating conditions that stimulate the latent seed bank.

Warm- versus cool-season grasses

The most productive agricultural soils in the Midwest are silty loams that accumulated significant amounts of organic matter under tallgrass prairie, which was dominated by warmseason grasses. These perennial grasses can have rooting depths of five to 15 feet compared to the

one to three feet of typical cool-season pasture grasses. The high species diversity of native prairies also contributed to supporting a robust soil microbial community. As a result, prairie soils had high levels of organic matter distributed far deeper into the soil profile than we see in clayey soils that formed under forests or sandy soils formed under barrens or desert plant communities (17).

Incorporating native perennial warm-season pastures into your grazing system can have many benefits. They are adapted to hot, dry conditions and can provide equivalent seasonal yields to cool-season

pastures during the 'summer slump' period when cool-season growth is lower. In addition, warmseason pastures can provide high quality wildlife and pollinator habitat. Challenges associated with warm-season pastures include high seed cost, slow establishment, and management differences compared to typical cool-season pastures, as well as lower overall forage quality (18). For more information on establishing and managing warmseason pastures, see the Green Lands Blue Waters warm-season pasture fact sheet (19).

Summary

Carbon sequestration in pasture soils is achievable, but is not a given for all situations. Your soil texture and the climate in your area are sometimes overriding factors, but you can adopt several management practices that promote increases in soil organic matter and carbon sequestration. Conversion of annual cropping to perennial pasture usually results in significant carbon sequestration, and grazing management practices that improve soil health, increase pasture plant diversity and rooting depth can promote continued increases in soil organic matter. While it may take a few years to establish and for benefits to accrue, adoption of all of these practices sets up a positive feedback loop where increasing soil organic matter can lead to improved water holding capacity, nutrient cycling, and productivity.

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Grassland 2.0 is a collaborative group of farmers, researchers, and public and private sector leaders working to develop pathways for increased farmer profitability, yield stability and nutrient and water efficiency, while improving water quality, soil health, biodiversity, and climate resilience through grassland-based agriculture.

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Green Lands Blue Waters is a vision for productive, profitable agriculture in the Upper Midwest based on the straightforward concept of getting as much value as possible from farmlands by growing crops that keep the soil covered year-round—what we call farming with Continuous Living Cover. The values from the crops we promote can be measured in yields and farm profits; but also as reduced risk, improved outlook for long-term productivity from the soil, more jobs, more wildlife, cleaner water, and resiliency in the face of a changing climate.

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