Impacts of Soil Health Management on Environmental Quality: A Research Review for Minnesota

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Background and Scope

This review was undertaken to summarize research on the impact of four in-field practices (cover crops, reduced tillage, perennials, and crop rotations) on nutrient losses, soil carbon, and runoff/erosion in Minnesota. Social, economic, and policy considerations, while highly relevant to agricultural decision making and design of incentives, are beyond the scope of this review. To maximize relevance of findings, this review focused on data from studies conducted in Minnesota, along with data from Wisconsin, Iowa, Michigan, South Dakota and Illinois if applicable. Since Minnesota has unique climatic conditions, findings from meta-analyses were not included, except as background or where regional differences were noted.

Since research on some of these topics, especially soil carbon, is still evolving, the information summarized cannot be considered a definitive assessment of the impacts of these practices on soil health. Attempts were made to highlight research limitations and sources of variation, but it was beyond the scope of this report to outline in depth the current research challenges and factors that affect results.

This report will help inform three efforts: (a) a **State Soil Health Action Framework**, funded by the McKnight Foundation through the MN Board of Water and Soil Resources (BWSR) and the Minnesota Office for Soil Health (MOSH); (b) a science synthesis to support updates to the **Nutrient Reduction Strategy**, led by the MN Pollution Control Agency (MPCA) with technical support from the University of Minnesota; and (c) the development of a **Soil Health Impact Calculator**, funded by BWSR through MOSH.

Executive Summary

Key implications

- Invest in cover crops that fit better into Minnesota systems. Incentivize them (especially rye) to support nutrient loss and erosion reductions, but do not necessarily expect a large increase in soil organic carbon. Also support and invest in cropping systems that facilitate cover crop use, such as shorter season corn and soy, small grains, and integrated crop-livestock operations.
- Reduced tillage includes a wide spectrum of practices including no-till, ridge till, and strip till, with varying benefits and impacts. Reduced tillage, already widely in use, should be supported for erosion control and other soil benefits, but not for soil carbon sequestration when implemented alone.
- Reduced tillage should be recommended for phosphorus loss reductions on many sites, especially sloping soils. It can increase losses in certain circumstances, so incentives should be nuanced.
- Perennials are possibly the single most effective strategy to reduce nutrient losses and erosion and increase soil carbon. Varieties, adoption, and markets are still developing, and research should be supported. In the meantime, alfalfa, agroforestry, prairie strips, managed pasture, and other perennial strategies should be supported as much as possible.
- The impacts of more diverse crop rotations depend on the particular crops and timing, but including cover crops, winter annuals, and perennials can offer significant benefits for nutrient losses, erosion control, and potentially soil carbon.
- Existing research has focused on effects of single-practice implementation. However, stacking multiple practices in a single field or watershed may be more effective and offer greater benefits, including net carbon sequestration, than the current research suggests. A systems thinking approach is required to most effectively address the ecological-social-agronomic matrix of soil health.
- Specific agricultural practices may simultaneously have positive and negative impacts on the various environmental goals of reducing N loss, P loss, and erosion, and increasing carbon storage.

Summary of research implications by practice

Cover crops

Cover crops are particularly useful in reducing pollutants in warm, humid climates, but are less consistently reliable in colder drier climates due to challenges with season length and competition for soil water (Dabney et al. 2001). Since cover crops, especially rye, have well-supported benefits for reducing nutrient losses and preventing erosion and runoff, one of the most effective strategies for Minnesota might be greater investment in cover crop varieties that fit well into existing cold-climate cropping systems. Cover crops can also fit more easily into small grains and canning crop rotations, so incentivizing production for those crops, or shorter season hybrids of corn and soybeans, could also help increase cover crop use. Winter annuals including pennycress and camelina likely provide a nutrient retention benefit as well, though are not as effective as rye. One potential drawback is loss of soluble P from cover crops thawing after a winter freeze, but this may be balanced by retention of soil and sediment-bound P through reduced erosion.

Current evidence does not suggest that cover crops as a singular practice result in large increases in soil carbon, especially in a cold climate. They have numerous other benefits and may help cropping systems approach carbon neutrality, but as a standalone practice, more research is needed before we should consider them to be a major part of soil carbon sequestration strategies in Minnesota. Since cover crops are generally effective in reducing nitrate leaching, they can potentially reduce downstream denitrification and greenhouse gas (nitrous oxide) emissions.

Reduced tillage

One of the biggest benefits of reduced tillage, strongly and consistently supported by research, is a reduction in erosion and runoff volume by protecting the soil from rainfall impact. It also reduces total phosphorus losses on average - there is some variability - in part by reducing sediment associated P losses. Reduced tillage is not considered a strategy to reduce nitrate losses, as it can increase dissolved nutrient concentrations by leaving residue on the surface and can increase leaching losses by leaving soil macropore structures intact. Conservation tillage practices like strip and ridge till might offer the best of both worlds, and are probably some of the best approaches to promote, at least until we more clearly establish direction and magnitude of nutrient loss impacts on different soil types and climates.

Reduced tillage has a variable and small effect on soil carbon, sometimes having no impact and in other cases slightly increasing SOC in shallow strata. Potential for emissions mitigation and possibly net sequestration could probably be increased by combining reduced tillage with cover crops to maximize C inputs.

Perennials

Perennials are one of the most effective strategies for nutrient loss reduction, soil carbon increases, and erosion control, with strong research support for often striking results (although soil carbon increases still take time). The challenge lies in broader adoption, technical assistance, demand, and marketing for the products of perennial agriculture. Production support and markets are well established for alfalfa, but other perennial crops like Kernza perennial grain and oilseed silphium are earlier on in their development. Supporting continued research on these types of cropping systems and incentivizing their adoption is one of the best ways to address nutrient, carbon, and erosion goals in the long-term. Perennials can be incorporated into agricultural landscapes in many other ways, as well. Agroforestry, windbreaks, contour strips, silvopasture, and other strategies might be more feasible for many farmers than full-scale perennial crop adoption, but they can still provide many soil, water, and climate benefits. Feasibility also depends on profitability of the land for row crops. Fields or areas where row crops are less profitable could be ideal for low-management crops like certain perennials.

Rotations

The impacts of rotations are difficult to separate from the benefits of the cover crops and perennials that might be included in them. However, the limited amount of Minnesota-relevant data that was available suggest that diverse or extended rotations are helpful in both nutrient loss and erosion reduction. Impacts will naturally depend on the exact system used. Even less research is available on soil carbon impacts of rotations, but this also would depend on which crops were used and for how long. Including perennials, cover crops, and winter annuals in rotations would presumably support nutrient loss, carbon, and erosion goals.

Common questions

Why do some reports indicate significant soil carbon gains under cover crops and reduced tillage, but this report does not?

On average, cover crops have a small positive effect. In MN, cover crop effects will be especially small due to short growing season, so global or national estimates are generally over-optimistic for C sequestration in MN with cover crops. For reduced tillage, many older studies found increases in soil C, but the newest data does not, and here we report the current scientific consensus that tillage regime has a minimal effect on soil C stocks.

Under what conditions is no-till more likely to result in net reductions in sediment and nutrient losses?

No-till generally decreases erosion and thus sediment-associated nutrient loss. However, since nitrate is soluble, no-till isn't a strong factor in predicting N losses unless used in combination with practices which retain N, like cover crops and precision N applications. There are already some existing guidelines on this, but more research is needed.

What is the impact of combining practices for soil carbon and other parameters?

There is a research gap around the soil carbon benefits of combining practices such as reduced tillage and cover crops. When implemented alone in a Midwestern climate, both tend to have minimal impacts, but more research is needed that looks at combined practices in realistic field settings.

How quickly can we see soil carbon gains from practices like cover crops and reduced tillage?

Current measuring technology and natural variability in soils and sites makes it difficult to determine exactly how much and how quickly soil carbon is being added. At least 3-5 years is a good baseline for gaps between measurements in order to capture likely changes, with careful, consistent sampling.

When is rye most effective as a cover crop?

Rye is one of the most effective cover crops in corn-soybean systems, often reducing nitrate losses by 30 to 50%, but sometimes by very little. Everett et al. (2019) reported a range of 4% to 67% soil nitrate N reduction across 19 sites in the Upper Midwest.

Cover crop effectiveness is highly dependent on successful germination and the amount of biomass produced, which depends on both weather and management factors. Planting and termination date (and method) are key. Other site factors, such as soil type, are also important. For example, mollisols have a high N mineralization capacity relative to other soils and decomposition and mineralization will occur rapidly.

Specific Nutrient Loss Reductions

Background

Annual row crop production results in large nutrient losses to the environment through leaching, runoff, and erosion (Robertson 1997). Note that the largest P loss pathway is usually sediment, while the largest N loss pathway is usually leaching of soluble nitrate. Annual systems including corn-soybean and corn-soybean-wheat rotations often lose 25 to 50 kg nitrate-N/ha annually, but can lose as much as 146 kg (Kaspar et al. 2007, Feyereisen et al. 2006 Syswerda et al. 2012; Snapp et al. 2010). Losses vary with fertilizer application levels, organic versus conventional management strategies, and tillage regimes, complicated by the short duration and small scale of many of the studies (Syswerda et al. 2012). Nitrate losses are complicated by both controllable factors - cropping system, rate and time of N application, nitrification inhibitors, tillage, tile drainage - and uncontrollable factors, including precipitation and soil mineralization (Randall and Goss 2008). When determining policy incentives for practices, it is important to understand which factors affect which nutrient losses, and how uncontrollable factors can change the efficacy of those practices. In some cases similar practices could result in very different outcomes due to site-specific variation, and different outcomes for N vs. P losses.

In Minnesota, subsurface drainage is a major loss pathway for soluble nitrate, and is concentrated in April through early June (Gast et al. 1978). Seventy-one percent of total drainage and 73% of total nitrate losses in a Minnesota study occurred in April, May, and June (Randall 2004). In general, nitrate losses are greatly affected by annual precipitation, high-flow events, and wet-dry cycles (Randall and Goss 2008).

Policies should support practices that result in living cover in the ground in the spring. Climate change could affect this by altering temperature and precipitation patterns; for example, heavier fall rains could occur, in which case strategies should be adapted.

Several studies highlighted the importance of soil test P (Hussain et al. 2021, Zopp et al. 2019) in predicting P losses. Reduced tillage can in some cases help prevent P losses, but given the apparent variability in its effects, it is also important to emphasize soil P testing and appropriate fertilizer application rates, including P-based manure application rates.

Cover crops

Nitrate

Overall, cover crops take up soil N and transform it into organic N, which is less likely to be lost. This is frequently demonstrated through lower spring soil nitrate levels, a major risk factor for nitrate leaching during periods of high spring precipitation. Cover crop type and the method and timing of cover crop termination also determine final impact. Cover crops that winter kill, such as forage radish, offer fewer benefits than those that survive the winter, because they do not continue nutrient uptake in the spring. Still, any cover crop can offer some benefits relative to fallow.

For non-legume cover crops, there is a relatively small range of tissue N concentrations, so higher biomass production usually results in the largest N uptake and immobilization. Root system architecture and mass also affects cover crop efficacy; in general the deeper and denser the root system, the higher the potential for nitrate uptake. Much cover crop research has focused on cereal rye, but barley, oats, annual ryegrass, and other grasses, as well as Brassicas including radish and turnip can also be used successfully. The key factor is a cover crop's ability to establish quickly and produce above and belowground biomass in cool conditions (Meisinger et al. 1991). Early establishment of the cover crop, including through interseeding, increases growth and subsequent N uptake.

Rye

Rye appears to be one of the most effective options for reducing soil and soil water nitrate in Minnesota. It is a winter-hardy crop and grows again in the spring, helping to prevent losses during the early part of the particularly high risk April - June period. Studies typically report 20-35% reduction in soil or soil water nitrate under a rye cover crop compared to annual systems (corn or soybean) without cover crops. Several studies reviewed also reported reductions of 50% or more, and a few found that rye cover crops had no or very little impact. Delaying rye harvest or termination until just before corn planting and high fertilizer rates were associated with largest reductions in soil nitrate or leaching losses due to rye compared to no cover crop.

- A rye cover crop terminated with herbicide in the spring reduced soil nitrate N by 35%, whereas harvested rye that grew for 3-4 more weeks reduced it by 59% (Krueger et al. 2011) compared to winter fallow in a dairy manure-fertilized silage corn system.
- Herbicide-terminated winter cereal wheat and rye (mid-late April termination) had higher spring soil nitrate than forage (harvested late-April to mid-May) or grain harvested treatments (mid-July). Despite receiving 52 kg N/ha at spring green up in March, the grain harvested treatments still had lower soil nitrate in June than the no cover treatment (Jewett and Thelen 2008).
- Rye terminated closer to the corn planting date also showed large reductions; in a no-till corn-soybean system, winter rye seeded near harvest and herbicide terminated 6-12 days before planting reduced nitrate concentrations and loads in all 4 years, on average by 59% and 61%, translating to a 31 kg N/ha reduction (Kaspar et al. 2007).
- A rye cover crop planted in a corn-soybean rotation resulted in larger nitrate loss reductions the longer it was in the ground. Planted on September 15 and desiccated at the end of May, it reduced N losses by 11.1 kg N/ha (45%). Planting on 1, 15, and 30 October resulted in reductions of 7.8, 5.8, and 4.6 kg N/ha, respectively. Earlier desiccation of the rye on May 1 resulted in reductions of 4.5, 2.2, 1.2, and 0.7 kg N/ha, for the 15 September and 1, 15, and 30 October sowing dates, respectively. A winter rye cover crop can reduce nitrate drainage losses on average by 7.4 kg N/ha for SW MN if planted on Sept. 15 and desiccated on May 15 (Feyereisen et al. 2006).
- On sandy loam soils in Michigan, inbred corn fertilized at 101 kg N/ha had low leaching losses (~7 kg N/ha), and rye took up little excess fertilizer. At 202 kg N/ha, more typical for corn, annual leaching losses were up to 88 kg nitrate-N/ha. Interseeded rye cover reduced this by up to 52 to 74% (Rasse et al. 2000).

Kreuger et al. (2011), Jewett and Thelen (2008), Kaspar et al (2007), and Feyereisen et al. (2006) show that termination timing and method have a large impact on total nitrate reduction. Nitrate can be released during the desiccation of plant material near the surface in the herbicide treatment, but when it is harvested, the cover may still be viable later into the spring, preventing mineralization of the plant residue as well as extending the window of nitrate uptake. Both methods appear to effectively take up and hold nitrate over the winter. Earlier herbicide termination offers a benefit of making more nitrogen available in the spring to meet corn needs and avoid yield losses, but has a higher risk for losses compared to rye harvested later in the spring for forage or grain. Ecosystem service payments could address the trade-off of higher corn yields vs. reduction in potential for spring nitrate losses.

Other studies found more moderate reductions.

- Rye injected with liquid manure following silage corn or soybean harvest reduced soil nitrate N by an average of 36%, with a range of 4% to 67% across the 19 sites studied (Everett et al. 2019).

- A system-level analysis of rye cover crop in corn found nitrate N losses reduced by 20%, or 31% per unit of N applied (Martinez-Feria et al. 2016).
- In west central Minnesota, a rye cover crop in a corn silage production system fertilized with dairy manure reduced spring soil nitrate by 46% and reduced the subsurface drainage nitrate concentration from 53 to 39 mg/L (Kreuger et al. 2013).
- No-till plus a rye cover crop decreased average spring nitrate loads by 11.8 kg/ha in chisel-till soy and 13.2 from chisel-till corn, but it did not consistently decrease loading from no-till treatments, which on their own had lower nitrate losses than chisel till. In other words, both a rye cover crop and no-till had benefits, but the benefits did not stack (Waring et al. 2020).

Rye cover crops are not always effective.

- In a corn-soybean rotation, rye was not effective in reducing nitrate loss (Qi et al. 2011), or reduced nitrate loss by just 11% on tile drained soil (Strock et al. 2004), although in Qi et al.'s experiment two years were drier than average, which may have prevented optimal establishment.
- A rye cover crop in continuous corn did not significantly reducing nitrate losses, but when combined with split N application (which also on its own did not significantly reduce losses), it reduced nitrate loss by 37% compared with pre-plant N and no cover crop (Preza-Fontes et al. 2021).

Other Cover Crops

Pennycress can be an effective cover crop, in addition to providing an additional income stream through harvest and sale as an oilseed. But agronomic best management practices and markets have yet to be finalized for this

- After sweet corn, which is harvested early and fertilized at high rates that tend to leave high levels of N in the soil, pennycress reduced soil inorganic N by 27-42% relative to no cover crop (Moore et al. 2020).
- A study assessing what authors termed "eutrophication potential" found that at two of three study sites comparing a corn-soybean rotation with and without cover crops, rye was most effective at mitigating nutrient losses, and at the other, which was not fertilized, pennycress and camelina were more effective (Cecchin et al. 2016).
- Winter rye, forage radish, field pennycress, winter camelina showed reductions in soil water nitrate-N during cover crop and intercropping phases, averaging 4 mg/L compared with 31 mg/L in fallow treatments, although there were differences between treatments. Since pennycress and camelina are fertilized winter cash crops, relative to rye, they showed higher soil water nitrate concentrations of ~15 mg/L. This was still less than half of levels in the spring and fall fallows (Weyers et al. 2019).
- In a follow-up study at the same site as Kaspar et al. 2007, oat and rye cover crops were seeded into living corn and soybean crops. Oat winterkilled in Nov/Dec and rye overwintered and was terminated with herbicide before main crop planting. Rye reduced drainage water nitrate concentrations by 48%; oat reduced them by 26%. Neither significantly reduced nitrate loads due to the variability in cumulative annual drainage among plots, but the lack of significance may be due more to high variability rather than a true lack of effect, especially since the previous study did indicate a large reduction. Nonetheless, it highlights the potential variability even in a highly effective cover crop (Kaspar et al. 2012).
- Using the Erosion-Productivity Impact Calculator, Meisinger et al. (1991) estimated reductions in nitrate leaching loads and concentrations for a humid Midwest climate typified by Ames, Iowa. Assuming fertilization rates of 87 to 107 lbs N/ac on a corn crop, sandy soil had load and concentration reductions of 64 and 50% with a barley cover crop and 45 and 50% with clover

relative to no cover crop. For a clay loam soil, predicted reductions were 67 and 50% for barley and 33 and 25% for clover.

- On eight research farms across Minnesota and eastern Wisconsin, corn planted after a cover crop and fertilized at 100 lbs N/ac had lower average annual tile drain water nitrate concentration, 3.14 mg/L, than to corn with no cover crop 12.83 mg/L, both) (Discovery Farm 2021).
- Perennial Kentucky bluegrass and creeping red fescue cover crops in a strip-tilled continuous corn system decreased the loss of total soil N (6.5%) relative to the no-cover crop controls (Banik et al. 2020).

Phosphorus

Cover crops can have more variable effects on phosphorus losses, in part because inherent soil erodibility plays a large role. They tend to be less effective in areas with a large amount of snowmelt runoff. This commonly occurs in flat areas such as the Red River Valley where winter runoff is the most critical pathway for P loss. Vegetation that is killed and flattened in the winter does little to reduce runoff, and the freeze-thaw cycles that result in snowmelt runoff events also cause plant cells to rupture, releasing P as well as, to a lesser extent, N (Mulla and Whetter 2020).

- In a corn-soy rotation fertilized with manure and followed by rye or oats, spring dissolved reactive P losses were higher, but fall total P losses were lower compared to the no-manure control (Kovar et al. 2011).
- Weyers et al. (2019) observed that while winter annual oilseed crops had a significant effect on soil and soil water nitrate, effects on reactive soluble P were not significant. Across four cover crop treatments, soluble reactive P ranged from 11 to 25 ug/L.
- In no-till silage corn fertilized with manure, spring P losses following fall manure application were lowest under rye and second lowest under ryegrass. Rye reduced P load by about 90%, ryegrass reduced it by 70%, and red clover by 58% relative to non-companion cropped treatments. Benefits were largely negated if manure was applied in the spring (Grabber and Jokela 2013).
- A rye cover crop had no impact on dissolved reactive P concentration in subsurface drainage water in a corn silage system in west central Minnesota (Krueger et al. 2013).

Reduced tillage

Tilling aerates the soil, increasing the availability of oxygen to microbes, and produces a burst of mineralization of soil organic matter (Dinnes et al. 2002). Mineralized forms of N are more vulnerable to leaching, as well as more plant-available. However, if crop plants are not taking up sufficient N shortly after tillage, or large precipitation events occur, N mineralized by tillage can easily be lost.

However, tillage has variable effects on nutrient losses, in part due to significant differences in the loss pathways of nitrogen and phosphorus. Nitrogen is largely lost as soluble, inorganic nitrate through groundwater leaching and surface runoff, though smaller amounts of sediment-bound N can be lost through erosion. Phosphorus is more likely to be lost in undissolved forms through sediment losses in eroded soil, but it can also dissolve in water and be lost through leaching and runoff. The forms in which P are lost are affected by fertilizer and manure application, tillage, cover crops, and the potential for erosion, runoff, and drainage as influenced by soil type, slope, and other factors.

Waring et al. (2020) mention multiple studies that found little or no impact of reduced tillage on nitrate-N concentration in subsurface drainage (Bakhsh & Kanwar, 2011; Fox, Zhu, Toth, Jemison, & Jabro, 2001; Logan, Eckert, & Beak, 1994). Others found reductions in N concentration but an overall increase in loading (Angle et al., 1984; Bakhsh & Kanwar, 2011; Gupta, Munyankusi, Moncrief, Zvomuya, & Hanewall, 2004; Tan et al., 1998), and some attributed nitrate concentration reductions to dilution from the increased drainage through macropores, or the impact of tillage on inorganic N available for leaching

(Finney, Eckert, & Kaye, 2015; Randall & Goss, 2008). Several studies, reviewed below, indicated some reduction in nitrate losses, but reduced tillage is generally not thought of as a nitrate-loss reducing practice.

A key question is if no-till facilitates more rapid infiltration and increased drainage – a plausible outcome if earthworm channels and other elements of soil structure are left intact. With increased drainage, reduced tillage can theoretically increase total nitrate leaching.

Ultimately, effects of tillage on nitrate losses are unpredictable on a large scale, making it difficult to incentivize as part of a nutrient reduction strategy. Even when accounting for known or controlled factors such as soil type, tile drains, fertilization regime, and cropping system, the impact still depends heavily on the amount and timing of precipitation and complex microbial processes. There is also a wide range of tillage types with very different impacts on plants, soil structure, and microbes (DeJong-Hughes and Daigh 2021).

Reduced tillage has more consistent benefits for reducing phosphorus losses, although there is some variability since it can both reduce sediment losses and increase dissolved nutrient losses. If the increase in soluble P concentration outweighs the reduction in erosion, reduced tillage can result in greater P losses; if not, it may reduce net losses. Soluble P losses are driven by leaving fertilizer and residue unincorporated on the surface, producing a stratification effect with high soil test P on the surface and reduced soil test P lower in the profile. Manure application represents a significant factor in P loss prediction; Zopp et al. (2019) found that timing of manure application and soil test P were sometimes more important than tillage in predicting P loss. Overall, reduced tillage can reduce P losses in many cases, especially in cases where sediment loss represents the primary P loss pathway.

Nitrate

Some studies found meaningful reductions in nitrate losses with reduced tillage.

- In a corn-soybean-winter wheat system in Michigan on loamy soil, nitrate loss was estimated (based on measured nitrate concentrations and modeled drainage) at 62.3 kg N/ha/yr for conventional management and 41.3 kg N/ha/yr for no-till (Syswerda et al. 2012).
- In a corn-soybean rotation comparing chisel plow and no-till, nitrate N load was on average 11.2 kg/ha per spring lower in no-till soy than chisel-till soy, and 9.9 kg/ha lower per spring in corn (Waring et al. 2020).
- Residual soil nitrate was higher under conventional than no-till in the 0 to 1.5 meter soil depth in five of eleven years of a study at sites in the Midwest. It did not differ in the other six years. Average nitrate concentrations were 13.4 mg/L under conventional and 12.0 mg/L under no-till. Subsurface drainage nitrate losses were 5% greater from tillage despite no-till having 12% higher drainage (Randall and Iragavarapu 1995).
- Conservation tillage increased residue cover, which led to lower total N sediment losses. Soluble nutrient losses were positively correlated with residue cover, but were small relative to sediment losses, so net losses were lower (Barisas et al. 1978).
- Ammonium and nitrate concentrations were generally higher under no-till than chisel or plow treatments, but the reduction in soil losses resulted in lowest nutrient losses from the no-till (Laflen and Tabatabai 1984).

Not all studies found that reduced tillage resulted in lower nitrate losses, despite lower nitrate concentrations.

- In a continuous corn system, average drainage water nitrate concentration under moldboard plow was 35.8 mg/L, significantly greater than no-till (22.2 mg/L) or ridge till (21.8 mg/L). However, more drainage occurred under no-till and chisel plow, so average 3-year losses were higher

under no-till (61.2 kg/ha) and chisel plow (64.3 kg/ha) than moldboard plow (45.8 kg/ha) (Kanwar et al. 1993).
- In a corn-soybean rotation, three-year average nitrate concentrations were 19.0, 13.4, and 13.9 mg/L in moldboard, no-till, and ridge till. Chisel plow had the highest nitrate losses (32.1 hg/ha), followed by moldboard plow (27.5 kg/ha), no-till (23.9 kg/ha) and ridge tillage (23.7) (Kanwar et al. 1993).
- Conservation tillage was not effective in reducing nutrient or water losses from annual cropping systems, even though it did reduce soil loss (Randall and Mulla 2001).

While no-till can in some cases result in a small reduction in nitrate losses, effects are inconsistent and more responsive to other variables including crop type, microbial activity, and climate. Thus, tillage policies to reduce nitrate leaching would need to be nuanced and graded in order to be effective, and even so it would likely be very difficult to estimate impact. While reduced tillage has many benefits and should be incentivized for other reasons, nitrate loss reduction efforts should probably focus on other factors.

Phosphorus

Several studies relevant to Minnesota showed a reduction in net P losses with reduced tillage.
- Chisel plow, till-plant, and no-till systems receiving the same amount of fertilizer reduced total P losses by an average of 81, 70, and 59%, respectively, compared to conventional till. They also reduced algal-available P by an average of 63, 58, and 27% respectively (Andraski, Mueller, and Daniel, 1985).
- Under conservation tillage, increased residue cover led to both higher available P content in the eroded soil and decreased soil loss, resulting in a net reduction in losses (Barisas et al. 1978).
- In runoff water from plow, chisel, and no-till management with simulated rainfall, phosphate concentrations were generally highest in no-till and lowest in plow. However, soil erosion was a much more important source of P losses, so total nutrient losses followed the opposite pattern: greatest losses in plow, then chisel, and least in no-till (Laflen and Tabatabai 1984).
- Across 125-site years of data from 26 Discovery Farm sites in Wisconsin and Minnesota, total and dissolved flow-weighted mean P concentrations were higher in runoff during frozen conditions in no-till fields, but total P losses during non-frozen conditions were lower in no-till fields. This was probably because lack of tillage reduced particulate-bound P loss, but led to higher dissolved P (Zopp et al. 2019).

In other cases, P losses were higher under no-till and reduced tillage.
- At a Discovery Farm site in Chisago County, Minnesota, median dissolved phosphorus losses were higher from the no-till site-years (0.56 lb/ac.) than from tilled fields at other Discovery farms (0.29 lb/ac.), although they are not statistically significant and are not a side-by-side comparison (Formo et al. 2018). This could be due to stratification of P in the soil or fertilizer or manure application rates. 61% of the losses at the no-till site were dissolved phosphorus, which was similar to median values in surface runoff across all 24 Discovery Farms, at which 54% of surface runoff P was dissolved and 46% was particulate (Discovery Farms 2016).
- In fertilized corn systems in Illinois, flow weighted concentration of dissolved P in no-till (0.34 mg P/L) was greater than in ridge-till, strip-till and fall moldboard, chisel, and sweep plow treatments, whereas moldboard and chisel plow treatments had low dissolved P, 0.06 mg P/L. Although there was less runoff with no-till, higher concentrations of dissolved P led to greater total loads than in other treatments (McIsaac, Mitchell, and Hirschi, 1993).

- In long-term no-till fields in corn-soy or corn-sorghum rotations, one-time moldboard plow tillage reduced dissolved P loss at both sites and reduced total phosphorus loss at one (Quincke et al. (2007b).
- Conservation tillage led to more snow accumulation and greater P loss from crop residues: 0.4 to 1.4 kg P/ha; 200 to 250% increase in total P load; 143 to 286% increase in DRP load (Hansen et al 2000).

The intensity of other field operations can also impact P losses.

- Low-disturbance injection of swine manure resulted in greater dissolved reactive P losses in both fall and spring than knife injection, but application method did not affect total phosphorus loads in runoff in either season (Kovar et al. 2011).

Impacts of tile drainage

Tile drainage can reduce surface runoff and erosion losses, but can increase leaching losses. Long-term no-till typically results in increased macropore development, since tillage is not disrupting preferential flow paths. No-till can also result in higher earthworm populations, which results in more macropore development as well. Tile drains also increase earthworm populations by helping avoid saturation, which can increase drainage even further when burrows connect to tile drain lines.

Since certain practices can carry different risks on nutrient loss on tile drained, vs. non-tile-drained fields, this should be taken into consideration in incentivizing tillage, cover cropping, and fertilizer management practices. For example, tillage can in some situations reduce nutrient losses. On a tile-drained clay soil with high shrink-swell capacity, applying manure to dry, untilled soil increases the risk of loss through cracks. Tillage before the manure application helps break up macropores and reduces the chances of loss into tile drains (Cooley et al. 2013).

Thus, while there are many reasons to incentivize reduced and no-till, a somewhat nuanced policy will be needed to maximize its benefits and ensure that negative outcomes are avoided.

Perennials

Nitrate

Perennials use N year-round, keeping generally lower nitrate concentration in soil and surrounding water. Options include alfalfa, CRP grassland, well-managed pasture or hay production, or perennial grain crops such as Kernza. Strong evidence exists for the nitrate leaching reduction potential of all these systems.

- Concentrations of nitrate in tile drainage water were 35 mg/L lower in alfalfa and CRP perennial grasses than in corn and soybean rotations (Randall et al. (1997).
- In an 11-year study in Michigan on loamy soil, annual corn-soybean-winter wheat systems lost 19.0 (unfertilized organic) to 62.3 (conventional) kg N/ha/yr, while alfalfa lost 12.8 and poplar lost less than 0.01 (Syswerda et al. 2012).
- Perennial bioenergy prairie systems had significantly lower flow weighted nitrate concentrations in drainage water than corn and soy systems, regardless of whether or not the prairie was fertilized: corn-soybean and continuous corn ranged from 6 to 18.5 mg/L; continuous corn with a cover crop averaged 5.6 mg/L; and prairie averaged <1 mg/L (Daigh et al. 2015).
- Beneficial effects of perennials (CRP and alfalfa) on subsurface drainage were negated in just 1-2 years after conversion to row crops, with residual soil N increasing by 125% after the first year following corn (Huggins et al. 2001).

- Mature miscanthus decreased N leaching by 42% and 88% compared to fertilized and unfertilized corn (Studt et al. 2021).

Multiple studies have indicated the potential of the long-rooted perennial grain crop Kernza to dramatically reduce nitrate leaching, even on sandy soils.

- Leaching under the perennial grain crop intermediate wheatgrass (Kernza) was 86% lower than under annual wheat (Culman et al. 2013).
- Leaching under intermediate wheatgrass was 96 to 99% lower than under corn at several sites around Minnesota (Jungers et al. 2019)
- In Minnesota's Central Sand Plain, average nitrate concentrations in soil water under intermediate wheatgrass stands were 77 to 96% lower than those under corn and unfertilized soybean (Reilly et al. in review.; Reilly 2021)

Phosphorus

Effects of perennial systems on P losses seem to be neutral or slightly positive. Largest reductions in losses will typically be observed in highly erodible soils with long-term perennial plantings.

- Total reactive phosphorus did not differ significantly between various corn-soybean systems and prairie harvested for biomass (Daigh et al. 2015).
- In Michigan, no-till corn (receiving 13 kg P/ha/yr) and unfertilized hybrid poplar, switchgrass, miscanthus, native grasses, and restored prairie did not differ significantly in P leaching, but P losses were positively correlated with soil test P. Seven-year cropping system means ranged from 0.035 to 0.072 kg P/ha/yr, lower than that at which eutrophication typically occurs (>0.2 mg/L), but higher than deep groundwater or uncontaminated lakes and streams. (Hussain et al. 2021).
- A modeling study focused on Southern Wisconsin found that replacing annuals with perennial energy crops along waterways decreased P loads to surface waters by 29% (Meehan et al. 2013).

Rotations

There is limited data available, but diversified rotations appear to offer nutrient loss reduction benefits.

- In a six-year field study in Iowa, diversified rotations (strip-intercropped corn-soybean-oats and alfalfa-corn-soybean-oats) had reduced flow-weighted average nitrate concentrations in subsurface drain water (6.5 vs. 11.2 mg/L) and reduced nitrate leaching losses (12.6 vs. 13.5 kg-N/ha) compared to a corn-soybean rotation (Kanwar et al. 2005).
- In a study combining ArcSWAT modeling and long-term field experiments total N losses were up to 39% lower and total P losses were up to 30% lower in the more diverse rotations (three-year corn-soy-oat/clover, and four-year corn-soy-oat/alfalfa - alfalfa) compared to a corn-soybean system (Hunt et al. 2019).

Soil Carbon

Certain agricultural practices can effectively increase soil organic carbon (SOC) stocks relative to other practices. In general, practices that increase carbon inputs into the soil through plant growth during a longer period of the year offer a potential to increase SOC. The amount of added carbon and the extent to which it remains in the soil in the long term depends on initial SOC levels, climate and soil type, and management practices including tillage, fertilizer, and irrigation. While measurements of soil carbon over time can link practices to net SOC changes, the net climate effect (or net CO_2-equivalent sequestration effect) must also take into account nitrous oxide, methane, and directly related CO_2 emissions. Nitrous oxide emissions are a major source of agricultural GHG emissions (Robertson et al. 2000) and can be affected by the same practices that increase SOC. Thus, while one management strategy may lead to an increase in SOC, that does not necessarily mean it has a net greenhouse gas (GHG) sequestration effect, since increases may not be maintained long-term, and because it does not reflect the many other potential sources of emissions generated by agricultural production. Ultimately, significant uncertainty still exists around soil carbon, and we need more research and improved sampling methodologies and models to better estimate net GHG impacts (Moore et al. 2021).

The potential of any annual cropping system to provide net C sequestration appears inherently limited. Robertson et al. (2000) found that none of the annual systems they evaluated, including no-till, organic management, and cover crops, provided net GHG sequestration; they all had positive global warming potentials. However, no-till had a much lower global warming potential than conventional tillage; 14 vs. 114 (measured in CO_2 equivalents). Cover crops also offered significant reductions, but not net negative effects. It is possible that combining these practices could result in net sequestration, or at least larger mitigation potential. More research is needed in this area.

Meaningful agricultural C sequestration on a large scale will require a fundamental shift, such as perennials and carefully stacked cover cropping, reduced tillage, and other conservation practices in all annual systems. Expanding perennial systems presents a challenge because until there are stronger markets and established supply chains for perennial grains like Kernza or perennial biomass for cellulosic ethanol, it is impossible to implement the most environmentally and climatically beneficial strategies on a large scale. Cover crops and reduced tillage can feasibly be implemented on a large scale, however, and if implemented together and along with other conservation practices such as agroforestry and prairie strips, could offer potential for meaningful carbon sequestration. We should still incentivize incremental practices, such as reduced tillage alone, we just shouldn't equate them with net carbon sequestration.

For any of these practices, length of implementation is key. Returning former cropland to an equilibrium SOC level close to pre-agricultural levels could take anywhere from 25-50 years (Jarecki et al. 2003), 55-75 years (in W. MN; McLauchlan et al. 2006), or 230 years (in MN sand plains; Knops and Tilman 2000), depending on soil type, climate, and other factors.

Conservation management practices need to be implemented on a long-term scale to achieve meaningful benefits.

In summary, cover crops and reduced tillage implemented separately probably offer reduced net emissions (mitigation) benefits, and well-documented climate adaptation and resiliency benefits, such as increased water holding capacity, but not net C sequestration. Perennial systems likely offer net C sequestration as well as climate resiliency and adaptation.

Cover crops

Studies on cover crops and soil carbon storage suggest that in general, cover crops increase soil carbon, but the magnitude of the increase is variable based on climate, cropping systems, and soil type. Global estimates of cover crop-related SOC increases range from 4% to 27% (Bai et al. 2019, Blanco-Canqui et al. 2015, McClelland et al. 2021, McDaniel et al. 2014), with estimates soil C gains of 0.1 to 1

Mg C/ha/yr (Poeplau and Don 2015, Blanco-Canqui et al. 2015). Gains are largest in warm climates with large cover crop biomass inputs, but are still significantly smaller than those observed under perennial systems.

Benefits can be maximized by combining cover crops with no- or low-tillage (McClelland et al. 2021, Bai et al. 2019, Blanco-Canqui et al. 2015). Given Minnesota's mostly annual systems, short growing window with limited biomass, and temperate climate, SOC increases are likely to be small (close to the 4% end of the range). Findings include:

- Perennial Kentucky bluegrass and creeping red fescue cover crops in a strip-tilled continuous corn system decreased the loss of total soil organic C (10.1%) relative to the no-cover crop controls (Banik et al. 2020).

While cover crops offer meaningful benefits for erosion control, soil structure, and even SOC, they should not be viewed as a carbon sequestration strategy when implemented alone. The magnitude of the potential increase is simply not high enough to be meaningful in a global climate context. Sequestration potential may be higher when combined with reduced tillage.

Since grass cover crops can be very effective in reducing nitrate leaching, they can potentially reduce downstream denitrification and greenhouse gas (nitrous oxide) emissions, and as such can be part of emissions reductions strategies. In some situations, legume cover crops can increase nitrous oxide emissions. Research and policy should address where this is likely to occur. Cover crops should be incentivized for a wide range of soil benefits, and included in GHG mitigation strategies including stacked practices and nitrate retention.

Reduced tillage

Six et al. (2002) describe four key fractions of SOC: silt and clay protected and microaggregate protected, both easily lost with cultivation; biochemically protected, and unprotected particulate organic matter. Reduced tillage probably helps reduce losses of microaggregate protected SOC, as well as unprotected fractions. However, it is unlikely to lead to SOC gains in Minnesota. In previous decades, research findings on reduced tillage and soil carbon gain reported positive results. Currently, consensus holds that SOC gains were limited to upper portions of the soil profile, and negligible for net C sequestration. However, there has been very limited research on the effects of combining reduced tillage with cover crops. Together, these practices may result in greater SOC benefits.

Robertson et al. (2000) reported that a no-till corn-wheat-soybean rotation in the Midwest accumulated 0.3 Mg C/ha/year, comparable to the 0.3 to 0.4 Mg C/ha/year sequestered by the perennial poplar and alfalfa systems. Gregory et al. (2005) also found that soil organic matter from 0-25 cm was higher in a no-till corn-soybean field (5.86%) than one with deep tillage (3.97%).

West and Post (2002) calculated an increase in soil C translating to about ~0.45 Mg C/ha/yr carbon sequestration, but not in all systems, and after about 20 years there was very limited impact. Another early study showed that no-till resulted in an increase in soil carbon by at least 10% across a range of sites (Ogle et al. 2005). A follow up study showed an increase in carbon at shallow depths (0-10) with no-till but an increase at greater depths (20-60) with tillage. It still suggested a net increase in soil carbon with reduced tillage, although not as large as initially thought (Angers et al. 2008).

Lou et al (2010) also found opposite effects in different strata, but no change in total soil carbon. Other studies supported the finding of no difference to full profile soil C (Baker et al. 2007, Haddaway et al. 2017) or no difference in 80% of cases (Christopher et al. 2009). In a review, Govaerts et al. (2009) found that SOC was equal in 40% of studies, increased in 50% of no-till studies (mostly in upper 30 cm), and reduced in 10%.

Blanco-Canqui and Wortmann (2020) and Quincke et al. (2007a) found that occasional tillage does not reduce soil organic carbon. Tillage every 5-10 years can help reduce compaction and stratification and aid weed control without losing the benefits of no-till. Similarly, Button et al. (2022) note that in certain soil types, deep plowing once over ten years or longer can help increase SOC, including soil with low very old SOC content, C-poor topsoil, high stone content, steep slopes, subsoil unfavorable to plant growth, and silty and Duplex soils.

Minnesota has multiple factors that make it unlikely to experience high SOC gains under reduced tillage. In a global meta-analysis, Bai et al. (2019) found that no- and reduced-till increased SOC more in warm climates and areas of low N inputs, neither of which applies to Minnesota. Liang et al. (2020) found that no-till can store carbon in semiarid climates, but not in cool and humid climates. There may be more potential for carbon gains on sloping soils, medium-textured soils, low C soil, eroded soils, coarse-textured soil with low biomass input, and when combined with cover crops. Thus, while Minnesota as a whole may not have a high potential for reduced tillage-induced SOC gains, certain areas with degraded soils and systems in which it is combined with cover crops might see greater benefits.

Current findings do not show that reduced tillage as a consistently effective strategy to sequester carbon on a large scale, but it should still be encouraged for soil health benefits including reduced erosion, increased SOM, water retention, and fertility, reducing impact of droughts and floods, possibly improving yields in semi-arid regions (Ogle 2021). Continued research on stacked practices and soil factors might also indicate where reduced or no-tillage has the greatest potential to conserve and even sequester carbon.

Perennials

A global review by McClellend et al. (2021) found that on average, perennial systems had 20% higher carbon stocks than annual systems. Perennials also increased SOC the most: 36% compared to 8% for annuals. Perennial grass fields have been found to maintain 43 Mg/ha more soil carbon than annual crops in the top one meter of the soil profile (Glover et al. 2010), and to store more each year than annuals: 0.32 to 0.44 Mg/ha/yr for perennials versus 0 to 0.3 Mg/ha/yr for annuals. This translates to a potential to sequester 0.20 to 1.05 Mg of CO2 equivalents per year under perennials, while annuals are likely to emit 0.41 to 1.14 Mg/ha/yr (Robertson et al. 2000).

Diversity also plays a role in SOC gain under perennials; in a Minnesota experiment net C accumulation was 0.69 Mg/ha/yr under a mixture of 16 native perennials and 0.4 Mg/ha/yr under perennial monocultures in the 1 meter soil profile (Fornara and Tilman 2008).

Increases in SOM under perennials are due to both the lack of tillage, which decreases decomposition rate, and an increase in organic matter inputs from belowground biomass (Kantola et al. 2017), which is positively correlated to net C accumulation (Fornara and Tilman 2008). Button et al. (2022) identify deeper roots as one of the most effective strategies to increase SOC, and perennials have two to four times as much biomass allocated to roots as annual plants (Dietzel et al. 2015). As root biomass turns over, that carbon, along with carbon in the form of root exudates, can be protected at depth and sequester carbon (Tiemann et al. 2015), allowing perennial systems to store much larger amounts.

The impact of perennials on soil carbon is emphasized by the impact of converting from harvested perennial grasslands to annual cropping systems, even no-till. Three years after a shift to no-till annual crops, DuPont et al. (2010) observed a 57% reduction in root biomass and significantly lower readily oxidizable carbon and microbial biomass in the 0-40 cm profile.

Current evidence suggests that perennial systems can increase soil carbon in the Midwest.

- Intermediate wheatgrass monocultures in Wisconsin added 0.54 to 0.58 Mg C/ha/yr; intercropped with red clover it added 0.46 to 0.52 Mg C/ha/yr. Once biomass removal and manure additions were taken into account, the monoculture accumulated 0.31 ± 0.09 Mg net C/ha and the biculture was carbon neutral (Wiesner et al. 2022).

- On sites with exposed subsoil near Webster, Iowa, switchgrass had 14 Mg/ha more root biomass than corn or soybean and the potential C input was 6.08 and 6.71 Mg/ha more than corn and soybean, respectively. Microbial biomass C was also 200% greater in the switchgrass cropping systems than in the corn–soybean rotation (Al-Kaisi and Grote 2007).
- Switchgrass fertilized at 112 and 224 kg N/ha on CRP land in Moody County, South Dakota, sequestered 2.4 ± 0.9 Mg C/ha/yr at the 0-90cm depth over four years. Unfertilized switchgrass did not show SOC changes over this time frame (Lee et al. 2007).
- A modeling study focused on Southern Wisconsin found that replacing annuals with perennial energy crops along waterways increased belowground C sequestration by 30% (Meehan et al. 2013).
- Culman et al. (2013) observed increased C mineralization, an important driver in carbon sequestration, in soils under intermediate wheatgrass.

However, it may take several years before that increase is detectable.

- At harvest, the intermediate wheatgrass had 1.9 times more straw C and up to 15 times for root C than annual wheat, but there were no significant differences in the size of the large or medium particulate organic matter C fractions, which are indicators of labile and more stable soil C pools. This study was conducted on sandy soils, which generally have a lower potential for C storage (Sprunger et al. 2018).

Rotations

SOC impacts obviously vary based on timing and exact nature of the rotation, but several studies suggest that it can increase soil carbon.

- Midway through a long-term experiment, particulate organic matter C was 1.86 g/cm³ in the two-year corn-soybean rotation; 2.44 g/cm³ in the three-year corn-soybean-oat/red clover rotation, and 2.38 g/cm³ in the four-year rotations corn-soybean-oat/alfalfa-alfalfa rotation (Lazicki and Wander unpublished data).
- Soil organic matter from 0-25 cm was higher in a 5-year rotation of corn–soybean– oats/ alfalfa–alfalfa–alfalfa rotation with tillage 2/5 years (7.81%) than a conventional corn-soy field (3.97%) (Gregory et al. 2005).
- A meta-analysis of soil C impacts found that while continuous corn increased SOC by 8%, a multi-crop rotation increased it by 12%, and a perennial system increased it by 35% (McClelland et al. 2021).

Sediment/Runoff/Erosion

Cover crops

Cover crops reduce erosion through multiple mechanisms: protecting the soil from wind and raindrop impact, creating a rougher surface that helps intercept runoff and decrease its velocity, reducing soil aggregate detachment and promoting water-soluble aggregate formation, and increasing opportunity time for water infiltration (Blanco-Canqui et al. 2011).

Blanco-Canqui et al. (2015) reported in a review study that cover crops can reduce runoff by up to 80% and reduce sediment losses by 40 to 96%. Effect size depends on both biomass and cover crop species, and cover crops have a greater effect after a low-residue summer crop such as silage corn or soybeans, which leave soil vulnerable to erosion. Overall, studies relevant to Minnesota suggest a moderate to large benefit of cover crops for erosion and runoff reduction.

- On sloping fields following no-till soybean, rye reduced rill erosion by 86 to 93%; oats reduced it by 42 to 64% compared to the control (Kaspar et al. 2001)
- In no-till silage corn, spring surface runoff and sediment losses following fall manure application were lowest under rye and second lowest under ryegrass. Rye decreased runoff volume and sediment load by ~90%, and ryegrass by ~70%. Red clover decreased sediment load by 57% and runoff volume by 43% (Grabber and Jokela 2013).

Tillage

Generally, reduced tillage appears to be very effective in reducing erosion and runoff.

- At a Discovery Farm site in Chisago County, Minnesota (well-drained Cushing loam with no tile; avg. slope 3.4%), no-till planting appeared to significantly reduce median annual soil loss compared to other Discovery Farm sites around the state. Over six years, the median no-till loss was 69 lbs/ac, whereas the median tilled loss was 260 lbs/ac (Formo et al 2018).
- Ridge tillage had lower rainfall runoff compared to moldboard plow for all three years of a study. In one year, sediment loss from ridge tillage was 53 times lower than from moldboard plow, largely due to a single heavy runoff event on July 4. In the following year, sediment loss was 12 times higher from moldboard plow than from ridge till (Gintig et al. 1998).
- Runoff volume from conventional corn-soybean fields was ~35 times higher than no-till corn-soybean no-till (Gregory et al. 2005).

Less commonly, it led to more runoff and sediment loss.

- Conservation tillage led to more snow accumulation resulting in a 46 to 281% increase in runoff and an 88 to 250% increase in sediment load (Hansen et al 2000).

Perennials

Perennials reduce runoff and erosion for the same reasons as cover crops.

- Replacing row crops with switchgrass reduced water runoff by 5.0 to 8.7% and soil loss by 43.7 to 89.4% in Eastern and Central till prairies and loess hills of Iowa and Minnesota, varying by region and hillslope (Wang et al. 2020).

Rotations

There is limited data on impacts on rotations on runoff and erosion, but results are generally positive, especially if rotations lead to more seasons with residue or living coverage during vulnerable times of year (spring and fall, open winters)

- Diversified 3 and 4-year rotations (corn - soy-oat/clover and corn-soy-oat/alfalfa - alfalfa) reduced erosion losses by up to 60% compared to corn-soybean, based on long-term field data and modeling (Hunt et al. 2019).
- Runoff volume from conventional corn-soybean fields was ~60 times higher than that from a 5-year rotation of corn–soybean–oats/ alfalfa–alfalfa–alfalfa rotation with tillage 2/5 years (Gregory et al. 2005).
- Ton/acre erosion losses in 2, 3, and 4-year rotations (corn-soybean, corn-soybean-oat/red clover, and corn-soybean, and corn-soybean-oat/alfalfa-alfalfa) were 1.36, 1.08, and 0.88, respectively; the three and four year rotations resulted in 20.5% and 35.3% reductions (Lazicki and Wander, unpublished data).

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In addition, the author reviewed the following presentations on soil carbon, tillage, and cover crops:

- Soil carbon sequestration: When is cover cropping an effective practice?
- Soil carbon sequestration: When does increased soil C storage yield net removal of greenhouse gases?
- Soil carbon saturation: do soils have a carbon storage limit, and if so, what controls it?