Carbon Sequestration Potential on Agricultural Lands: A Review of Current Science and Available Practices

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Executive Summary

Carbon sequestration on agricultural lands is possible through a range of soil management strategies and could be substantial with widespread implementation. Sequestration of historic carbon emissions is now essential as mitigation alone is unlikely to stabilize our atmosphere. There are numerous management strategies for drawing carbon out of the atmosphere and holding it in the soil. These strategies vary in effectiveness across different climates, soil types, and geographies. There are still debates about the durability of sequestration in soil and about the precise conditions that maximize drawdown of carbon emissions. This paper explores how soil carbon is sequestered, the state of soil carbon research, and the debate on the extent of its potential. It offers a set of recommendations for ongoing research and highlights the many co-benefits to increasing soil carbon.

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Introduction

Recent reports from the Intergovernmental Panel on Climate Change (IPCC) suggest that even if substantial reductions in anthropogenic carbon emissions are achieved in the near future, efforts to sequester previously emitted carbon will be necessary to ensure safe levels of atmospheric carbon and to mitigate climate change (Smith et al. 2014). Research on sequestration has focused primarily on Carbon Capture and Storage (CCS) and reforestation with less attention to the role of soils as carbon sinks. Recent news reports of melting glaciers and ice sheets coupled with a decade of record-breaking heat underscores the importance of aggressive exploration of all possible sequestration strategies.

Soils have the potential to sequester carbon from the atmosphere with proper management. Based on global estimates of historic carbon stocks and projections of rising emissions, soil's usefulness as a carbon sink and drawdown solution appear essential (Lal, 2004, 2008). Since over one third of arable land is in agriculture globally (World Bank, 2015a), finding ways to increase soil carbon in agricultural systems will be a major component of using soils as a sink. A number of agricultural management strategies appear to sequester soil carbon by increasing carbon inputs to the soil and enhancing various soil processes that protect carbon from microbial turnover. Uncertainties about the extent and permanence of carbon sequestration in these systems do still remain, but existing evidence is sufficient to warrant a greater global focus on agricultural soils as a potential climate stability wedge and drawdown solution. Furthermore, the ancillary benefits of increasing soil carbon, including improvements to soil structure, fertility, and water-holding capacity, outweigh potential costs. In this paper, we'll discuss the basics of soil carbon, how it can be sequestered, management strategies that appear to show promise, and the debate about the potential of agricultural soils to be a climate stability wedge.

Soil Carbon 101

Carbon Cycles

Carbon is constantly cycling between different global carbon pools as it changes molecular forms. Photosynthesis and the subsequent use of its byproducts by other organisms cycles carbon between the atmosphere into forests, soils, and oceans, while human energy consumption cycles carbon from fossil fuel pools to the atmosphere. As carbon flows between them, each of these different pools has the capacity to be either a source or a sink. Carbon sinks are pools that accumulate more carbon than they release, while carbon sources release more carbon than they accumulate. Understanding source/sink dynamics and how to optimize the capacity of sinks to draw and keep carbon out of the atmosphere is crucial to reversing anthropogenic climate change. Currently the atmosphere and ocean have too much carbon while soils have lost carbon at an alarming rate due to development, conversion of native grasslands and forests to cropland, and agricultural practices that decrease soil organic matter.

Estimates of the precise size and annual net change in carbon pools vary, but the relative sizes of each primary planetary pool of carbon – oceans/aquatic systems, vegetation, and soils - are well understood. Oceans and aquatic systems are by far the largest at an estimated 38,000 gigatons (Gt) and vegetation is the smallest of the pools at an estimated 650 Gt. Soil is about four times the size of the vegetation pool at an estimated 2500 Gt, making it the largest terrestrial pool of carbon (Batjes, 1996).

What is Soil Carbon?

Although some soil carbon comes from mineral sources, the vast majority of it is derived from plants. As plants grow and die, they leave behind organic, carbon-based compounds in the soil of varying size and chemical composition. Under the right conditions, soil fauna metabolize these compounds, incorporating some of the carbon in them into new chemical compounds within their own biomass, while respiring the rest to the atmosphere as CO2 or excreting it back into the soil.

This continuous movement of carbon through the soil food web means that carbon is constantly changing forms in the soil as it is incorporated into new organisms or converted into different compounds. Soil scientists classify carbon into general categories or pools based on how long the carbon remains in the soil, a figure often referred to as "mean residence time." The most commonly used model of these pools includes three different groupings: the fast or labile pool, the slow pool, and the stable pool (Jenkinson and Rayners, 1977).

The fast pool is soil carbon that turns over and returns to the atmosphere sometime within a few days to a few years. Carbon in this pool is typically composed of recently incorporated plant residues and simple carbon compounds that are exuded by roots. This labile pool is the one most readily used by soil microbes, meaning it generates a great deal of CO_2. The slow pool is composed of more processed plant residues, microbial byproducts of the fast pool, and carbon molecules that are protected from microbes by physical or biochemical soil processes. Mean residence time of the slow pool is generally considered to be in the range of years to decades, but this range can be heavily influenced by soil texture, management, and climate. In contrast, the stable pool is more resistant to disturbances and is extremely slow to change, with mean residence times ranging from centuries to millennia. This pool is comprised of what is often called humus, a loose term for a group of carbon compounds that are extremely resistant to decomposition, and soil carbon that is very well protected from microbial decomposition (Six et al., 2002). The relative size of each of these pools can vary in different soils. But in general, the size of the stable pool remains relatively constant, while the sizes of the labile and slow pools are sensitive to management.

How is Carbon Sequestered in Soils?

Since the size of the stable pool is generally static, soil carbon is effectively increased in the labile and slow pools by increasing the net balance of carbon that enters the soil every year relative to what is lost. Agricultural managers can strongly influence this dynamic in four ways:

1.) Decreasing the level of soil disturbance (i.e. tillage) to enhance the physical protection of soil carbon in aggregates.

2.) Increasing the mass and quality of plant and animal inputs to soils.

3.) Improving soil microbial diversity and abundance.

4.) Maintaining continuous living plant cover on soils year-round.

Managing these processes can quickly lead to increases in soil carbon that may be highly useful in drawing down atmospheric CO_2. The extent and permanence of soil-based carbon sequestration is currently under investigation and debate. Some of these contested issues are covered more completely in the following sections.

Aggregation/Physical Protection

One of the most important ways carbon is sequestered in soils is through the process of soil aggregation. Soil aggregates are formed when smaller soil particles adhere together into larger, more stable groups, bound together by clay particles present in the soil and glue-like substances generated by microbes decomposing organic matter, such as glomalin produced by arbuscular mychorrhizal fungi (Oades, 1984; Six et al., 2004; Wilson et al., 2009). As these aggregates form, small particles of carbon, such as partially decayed plant residues, are captured in the center of the aggregates. At the center of these aggregates, these carbon rich materials are physically protected from microbial attack. Microbes cannot penetrate the center of these stable aggregates, and conditions at the center, where oxygen and water are low, discourage microbial metabolism (Six et al., 1998, 2000). When aggregates remain stable and undisturbed, they can protect soil carbon for very extended periods of time. However, tillage can quickly break apart aggregates, exposing soil carbon to microbial attack (Grandy and Robertson, 2006, 2007).

Chemical Protection/Organo-Mineral Complexes

In addition to physical protection of soil carbon through aggregate formation, carbon compounds can be chemically protected from decomposition. The ability of a soil to chemically protect carbon molecules is highly dependent on the proportion of the mineral fraction of soil that is comprised of clay. The surfaces of clay particles are strongly negatively charged. As the microbial community processes carbon molecules, some of the byproducts they produce have strong positive charges. When these molecules make contact with clay particles, they can form strong bonds, effectively protecting the molecules from microbial attack. This form of chemical protection is highly effective and helps to explain why higher soil carbon content and clay are correlated worldwide (Jobbagy and Jackson, 2000; Six et al., 2002). Unfortunately, since producers by and large cannot change the clay content of their soils, the potential for this type of sequestration relies more on existing soil resources than modifications to management strategies. However, soils with high clay content are often much more responsive to soil carbon sequestration interventions, thus efforts to take soil-based carbon sequestration to scale could target and prioritize arable land with high clay content.

Increasing Quantity and Quality of Inputs

Aside from finding ways to protect soil carbon from microbial attack through chemical and physical protection, producers can simply change the soil carbon balance by increasing the amount and chemical complexity of carbon inputs to offset losses due to microbial respiration. In many annual cropping systems, soil is left bare following crop harvest, meaning that for a large portion of the year no biomass production is occurring on that land. In terms of carbon cycles, lower annual biomass production means significantly lower carbon inputs to the soil, making it more difficult for producers to compensate for the soil carbon losses they experience throughout the year. Increasing average annual biomass production through the use of cover crops or periodic green fallows could tip the balance towards a net gain of carbon rather than a loss (McDaniel et al., 2014; Tiemann et al., 2015). Introducing plant diversity to crop rotations and using legume cover crops, which contain carbon compounds likely more resistant to microbial metabolism, could also increase the complexity and diversity of soil carbon, making it more stable (Wickings et al., 2012). These strategies greatly increase the total amount of aboveground biomass entering agricultural systems, but enhancing belowground biomass by increasing the production of roots may be even more important. Annual cropping systems are often dominated by plants with shallow rooting systems. Kell (2012) argues that focusing on breeding crop plants with more extensive root systems could increase the potential of agricultural systems many times over. Introducing cover crops with deeper roots could maximize the amount of belowground biomass, and groups like the Land Institute (Salina, KS) are actively working on developing deep-rooted perennial cereal crops that could produce much larger quantities of belowground biomass while still producing food.

Soil Biology

Soil microorganisms play a crucial role in the carbon sequestration process by transforming plant residues into smaller carbon molecules that are more likely to be protected and sequestered (Six et al., 2006). Mesovores, which include soil-dwelling insects, worms, and nematodes, are responsible for processing larger pieces of plant residues into smaller forms that can be metabolized by smaller organisms such as fungi and bacteria. At each point on this decomposition pathway, different types of carbon of differing size and chemical complexity are produced that can be associated with silt and clay particles or incorporated into soil aggregates (Six et al., 2006; Grandy and Neff, 2008; Grandy and Wickings, 2010).

Soil fungi play an additionally important role in soil carbon sequestration by maximizing the amount of carbon allocated to the soil and producing compounds that improve aggregate stability. Arbuscular Mychorrizal Fungi (AMF) form mutualistic associations with plant roots, providing plants with soil nutrients while plants provide AMF with simple sugars (Govindarajulu et al., 2005). As plants feed AMF, their biomass increases effectively increasing the amount of carbon the process of photosynthesis provides to the soil (Rillig et al., 2001). AMF also produce a very sticky protein called glomalin that helps to bind soil aggregates together, helping to protect soil carbon (Rillig, 2004). In a long-term manipulation of field experiments to produce a gradient of AMF abundance, Wilson et al. (2009) found that AMF was strongly positively correlated to soil aggregation and carbon levels.

In addition to soil fungi, soil bacteria play an important role in processing organic matter. Nitrifying bacteria convert complex nitrogen compounds from organic matter into forms that are more available for plant uptake, while *Actinomycetes* are responsible for the decomposition of highly recalcitrant forms of carbon, such as lignin. These decomposition processes are essential to both and maximizing biomass production and ensuring that carbon is converted into stable forms that remain protected in soil (Six et al., 2006). Managing soils for abundant soil microorganisms by providing sufficient and diverse plant inputs and by reducing tillage can vastly improve the capacity of soils to sequester carbon (Six et al., 2006).

Soil Carbon Saturation

While the capacity of soil carbon sequestration is potentially immense, soils can reach a carbon saturation limit. At saturation, a soil will cease to be a sink and can either become a CO_2 source or reach a steady state wherein it draws in as much carbon as it emits on an annual basis. The saturation point of a given soil was described by Six et al. (2002) as the point at which the soil carbon protecting processes of aggregation, adhesion to mineral particles, and biochemical protection cease to protect new carbon. Any additional carbon, then, might be considered "free" and vulnerable to microbial attack.

Inherent soil characteristics, such as clay content and type, have a strong influence on these processes, and therefore a strong influence on a soil's saturation limit. But the majority of soils around the world are likely well below their saturation limit because of poor management and degradation (Lal, 2004). Deep soil well below the surface may be even further from saturation since roots do not often penetrate to subsurface levels (Kell, 2011, 2012). Saturation limits, though, mean that the global potential of soil to act as a carbon sink is finite. Soil carbon sequestration cannot continue indefinitely, and management typically affects the first meter or less. Nevertheless, the majority of soils around the world are far from being carbon saturated and would greatly benefit from increased carbon inputs.

Impacts of Fertilizers on Soil Carbon

The advent of fertilizers in agriculture has dramatically increased global agricultural productivity and simplified management by providing crops with readily available nitrogen, an element essential to plant growth. But from an ecological perspective, this shift in management represents an enormous change in the nutrient balance in soil ecosystems with a potential to affect soil carbon dynamics. Studies have found that chronic nitrogen additions to soils in both natural and agricultural systems decrease soil microbial activity (Marschner et al., 2003; Bowden et al., 2004; Ramirez et al., 2012; Frey et al., 2014). These results are unusual since we might expect that large increases in available nutrients would in fact increase activity, but it may be related to changes in plant communities and their interactions with soil microbes. Plants that receive fertilizer do not need as extensive root systems to mine for nutrients, reducing their capacity to excrete root exudates that increase soil microbial biomass.

A number of studies have also found that soil CO_2 respiration is reduced in chronically fertilized systems, and that turnover of highly recalcitrant soil carbon is reduced. Other studies have also found, however, that chronic fertilizer additions increase turnover of the labile soil carbon pool (Neff et al., 2002), compounds that are often recently derived from plants and are important to increasing soil carbon pools over time. Thus, the ultimate effects of continuous nitrogen fertilization on soils are complicated and remain unclear. Fertilization may simultaneously protect one soil carbon pool while limiting the ability of soils to increase another. This shift in dynamics is further complicated by the fact that fertilization can increase the total amount of plant biomass produced in agricultural systems, which eventually supplies soils with more carbon. Regardless, given the massive scale on which fertilization takes place, a more complete understanding of how nitrogen fertilizer additions will ultimately affect the capacity of soils to sequester carbon in the long-term is essential to understanding the capacity of agricultural soils to act as a sink for atmospheric carbon.

Agricultural Systems that Could Sequester Carbon

Scientific interest in understanding what types of agricultural systems increase soil carbon and how has generated huge amounts of research on a variety of systems and on carbon dynamics in agricultural systems at different scales. Several agricultural systems have emerged as having the potential to increase soil carbon, although important details about the permanence of the carbon they sequester should be carefully considered.

Conventional No-Till and Conservation Tillage

Among the most widely studied agricultural management strategies that can increase soil carbon are no-till systems. No-till is a system used on over a third of US crop acres that generally relies on specialized planting equipment, chemical herbicides, and genetically modified seed to reduce or eliminate the need for tillage equipment. Since soils in these systems remain undisturbed, soil aggregates remain intact, physically protecting carbon. Several studies have demonstrated that no-till can increase soil carbon rapidly, especially at the soil surface (West and Post, 2002), and several more detailed studies have found that this increase in carbon is linked to increases in aggregation (Cambardella and Elliott, 1992; Six et al., 2000). However, in order to maintain gains in soil carbon, it is important to continuously manage soils with no-till. Grandy and Robertson (2006) found that tilling a previously untilled soil quickly reversed nearly all the previously recorded gains by disrupting aggregates and exposing carbon molecules to microbial attack.

Similar to no-till, conservation tillage utilizes tillage implements less aggressive than the classic moldboard plow and requires fewer tillage passes per season such that more residues are left on the surface and disruption of soil aggregates is reduced. This approach also generally relies on chemical herbicides and genetically modified seed to reduce weed pressure. Although conservation tillage comes in many forms, several studies have demonstrated that it also can increase soil carbon by increasing soil aggregation and physically protecting carbon, but sequestration generally occurs at rates lower than no-till (Doran, 1980; West and Post, 2002; Halvorson et al., 2002).

The large number of studies on carbon sequestration in no-till and conservation tillage systems seem to have generated some consensus that both these approaches can increase soil carbon. But a handful of recent meta-analyses have cast doubt on the extent of their potential. Powlson et al. (2014) and Baker et al. (2007) both highlight that the majority of studies on no-till and conservation tillage primarily demonstrate differences in carbon concentrations at the soil surface, while ignoring lower depths where more aggressive tillage systems, such as moldboard plowing, may actually be relocating carbon. Syswerda et al. (2011) demonstrated that when sampled to more extensive depths, no-till still outperformed conventional tillage systems. But a lack of data comparing soil carbon levels at depth in no-till systems versus other tillage systems from other similar trials may suggest the research community is overestimating the effectiveness of no-till systems to sequester carbon.

It is also clear that since the carbon accrued in these systems is largely due to physical protection, maintaining the same tillage regimen is important to ensuring that carbon remains sequestered. Although adoption of these strategies has increased amongst grain producers, especially in North America, anecdotal evidence suggests that many producers do not actually utilize no-till or conservation tillage every season, preferring to periodically till their soils with more aggressive implements to prevent problems such as compaction and to combat weeds (Grandy et al., 2006). Furthermore, the heavy reliance on herbicides and fertilizers can negatively impact water quality, and the repeated use of glyphosate has produced a number of glyphosate-resistant weeds that often require tillage to be controlled (Duke and Powles, 2008). The potential lack of permanence of soil carbon in many conservation tillage or no-till regimes coupled with the problems presented by their extensive reliance on herbicides raises question about the utility of this approach for long-term carbon sequestration.

Organic No-Till

Since organic production systems are not allowed to use herbicides or chemical fertilizers and rely on cultivation to control weeds, reducing tillage in these systems is much harder than in their conventional analogues. Conservation tillage implements that plow to a limited depth and do not invert soil like a classic moldboard plow can reduce disturbance, but the need to make multiple passes with cultivating equipment to control weeds can offset the benefits of conservation tillage implements and lead to carbon losses.

Researchers at the Rodale Institute and a number of other institutions have been experimenting with an organic no-till system, however, that if successfully developed could hold promise. The system relies on an implement called a roller-crimper that is used to roll over a standing cover crop in spring, flattening and crimping plants so that they die, creating a mulch on the soil surface that will continue to suppress weeds throughout the growing season (Rodale Institute, 2015). Whereas most organic systems using cover crops will mow the cover crop to terminate it then till it into the soil, a roller-crimper avoids these steps, protecting the soil from disturbance. No long-term studies on the effects of this system on soil carbon pools are yet available, but soil modeling projections estimate that the carbon sequestration rates and full cycle carbon budgets, including external carbon costs, of organic no-till systems could outperform more conventional tillage systems (Ryan et al., 2009).

Researchers testing these systems have had to deal with significant issues of weed pressure and regrowth of cover crops that affect crop productivity (Mirsky et al., 2012). Key to terminating the cover crop effectively is rolling it at the correct developmental stage (Mirsky et al., 2009; Davis, 2010). Organic no-till may also affect soil nitrogen availability, as the large amount of plant biomass it requires can cause soil microbes to rapidly uptake soil nitrogen, making it unavailable to plants (Parr et al., 2014). Organic no-till is still only being researched and practiced on a limited scale, and producers and scientists are still searching for ways to overcome these issues. If reliable methods are developed, this system could lead to extensive carbon sequestration and many additional co-benefits.

Cover Crops and Crop Rotations

While conservation tillage and no-till rely on protecting soil from disturbance by tillage, other approaches simply compensate for the loss of carbon due to tillage by increasing carbon inputs from plants. The use of periodic green fallows, winter cover crops, and crop rotations that utilize semi-perennial crops, such as alfalfa, were practices long used in agriculture that fell out of use as synthetic fertilizers and pesticides became more widely used. Such practices have demonstrated benefits for weed suppression and soil fertility, and some evidence suggests that they can also lead to carbon sequestration.

In a long-term cropping systems experiment at the Kellogg Biological Station at Michigan State University, researchers found that over a 12-year period an organic management system that employed increased rotational diversity and extensive use of winter cover crops led to a significant increase in soil carbon, despite extensive tillage for weed control (Syswerda et al., 2011). Such results might be explained by a net positive difference in carbon inputs versus carbon respired as CO_2, as well as improved soil biological function.

In a recent meta-analysis, researchers found that more diverse crop rotations consistently have higher soil carbon and soil microbial biomass than less diverse systems, especially when cover crops were included in the rotation (McDaniel et al., 2014). Tiemann et al. (2015) further demonstrated that rotational diversity has important impacts on soil carbon accrual by improving the ability of soil microbial communities to rapidly process plant residues and protect them in aggregates. The inclusion of several different crops in a rotation also introduces a greater diversity of carbon compounds into the soil, some of which may be more resistant to decomposition. While previous thinking held that microbial processing of residues in soils eventually produced similar carbon pools and compounds, a recent laboratory experiment found that the initial chemistry of the plant residues and the microbial community had a strong influence on which carbon compounds are present in the soil (Wickings et al., 2012). The inclusion of a diversity of crops, then, might ensure that a diversity of carbon compounds is present in the soil, improving soil carbon sequestration potential.

Increasing cropping system diversity is a strategy that is relatively simple to implement in a technical sense in that it mostly just requires growers to plant cover crops or keep to a more consistent rotation of grain crops. Resistance to this strategy may be due to the dominance of monocultures in agriculture globally, the concomitant reduction in markets for alternative crops, and perceived risk in growing multiple crops. However, diverse crop rotations can meet the productivity of monocultures while improving environmental services and reducing the need for inputs (Davis et al., 2012).

Rotational Grazing

Recent research on grazing practices and production of meat animals, particularly cattle, has gained considerable attention for its carbon sequestration potential. When managed correctly, herds of grazing animals can maximize annual pasture biomass production and redistribute carbon throughout pastures in the more processed form of manure, leading to rapid increases in soil carbon. Methods such as Management Intensive Grazing emphasize frequently moving cattle to new pastures, high stocking densities, and preventing overgrazing such that pasture plants have continuously high biomass. In addition, this style of production generally does not require tillage, meaning soil aggregates are not disrupted and their carbon remains physically protected from disturbance.

The effectiveness of rotational grazing may be further enhanced by the addition of compost amendments to rangelands. Studies by the Marin Carbon Project in association with soil scientists from the University of California, Berkeley recently demonstrated that very thin applications of compost to grasslands under managed grazing led to substantial increases in plant biomass and a net increase in carbon sequestration (Ryals and Silver, 2012; Ryals et al., 2014). These results suggest that even small additions of composted organic matter can vastly improve the productivity of degraded rangelands and enhance their carbon sequestration capacity.

There are few studies evaluating the full carbon cycle of such systems. However a meta-analysis of the existing studies on how improvements to grassland management might affect soil carbon accrual found that in the majority of the studies, conversion from croplands to grasslands and improvements in management led to greater carbon sequestration (Conant et al., 2001). More recently, researchers working in the southeastern US found that converting land formerly in row crops to management-intensive grazing rapidly increased soil carbon to an apparent saturation point (Machmuller et al., 2015). They also estimated that the methane emissions of cattle from enteric fermentation were offset during the early phase of rapid carbon accumulation. More extensive research on the full carbon cycle of grazing operations, including fine-scale measurement of emissions in the form of methane from cows themselves will be necessary to properly evaluate the efficacy of this approach for soil carbon sequestration, but early results are promising.

Perennial Cropping Systems

The majority of cropping systems are dominated by annual plants that rely on cycles of tillage and planting of seed to ensure sufficient productivity. By comparison, perennial plants that are capable of surviving several seasons require less disturbance. Perennial cropping systems have been recently proposed as systems that could protect soil carbon well, and since perennial plants often rely on more extensive roots systems to ensure longevity, they likely produce more belowground biomass (Cox et al., 2006). Early efforts to breed perennial grain crops in the Soviet Union were moderately successful until abandoned (Wagoner, 1990). Groups like the Land Institute (Salina, KS) are currently reviving those efforts with good success, although cultivars ready for extensive commercial distribution are still several years off. The necessary field trials to demonstrate the carbon sequestration potential of these crops are yet to come, then, but perennial grains are conceptually promising. By comparison, agroforestry systems that utilize tree crops and are designed to mimic forested systems while still producing food could be readily implemented but are largely under-utilized and understudied. Albrecht and Kandji (2003) argue that the carbon sequestration value of agroforestry systems is potentially significant based on a review of the agroforestry literature.

Co-Benefits

In addition to mitigating carbon emissions, increasing soil carbon can have profound effects on soil quality and agroecosystem productivity. Soil carbon plays important roles in maintaining soil structure (Bronick and Lal, 2005), improving soil water retention (Rawls et al., 2003), fostering healthy soil microbial communities (Wilson et al., 2009), and providing fertility for crops (Schmidt et al., 2011). These improvements are well documented and have generated a consensus that improvements to soil carbon are key to improving agricultural systems as a whole. While uncertainties may remain about the potential of agricultural soils to act as a carbon sink, the vast number of co-benefits should remain an incentive to modify agricultural practices to increase soil carbon in their own right.

Reducing Other Greenhouse Gas Emissions in Agriculture

Aside from net soil carbon sequestration capacity, there are several other important considerations in evaluating agricultural systems for their climate mitigation potential and feasibility. While carbon dioxide is the largest driver of anthropogenic climate change, and has been the main focus of mitigation efforts, there are other greenhouse gases (GHGs) that make significant contributions to climate change. These gases, particularly methane (CH_4) and nitrous oxide (N_2O), are commonly emitted from soils and should be considered in studies of agricultural climate mitigation potential.

Agricultural activity is responsible for about 70% of anthropogenic N_2O emissions (World Bank, 2015b) and 40% of CH_4 emissions globally (World Bank, 2015c). These greenhouses gases have significantly higher radiative forcing and longer atmospheric residence times than CO_2. Although neither of these gases can be taken up directly by plants and sequestered in soils the same way as

CO_2, it is important to consider the emission of these GHGs when evaluating different agricultural practices for their potential to sequester carbon. Research on N_2O and CH_4 emissions is a relatively new field, but there are clearly a few factors that strongly influence emissions of either gas from soils.

N_2O emissions increase when soils become saturated with water, creating anaerobic (i.e. low oxygen) soil conditions in which bacteria are forced to use nitrate instead of oxygen as a final electron acceptor in metabolic processes, producing N_2O (Firestone and Davidson, 1989). Emissions are further increased when high soil moisture is coupled with high temperatures (Linn and Doran, 1984; Peterjohn et al., 1994). Emissions of N_2O therefore tend to occur in pulses that are strongly coupled with wetting/drying cycles in soils during the growing season. During these pulses, the total amount of nitrate in the soil strongly influences the total amount of N_2O emissions that will occur, meaning agricultural practices that tend to saturate soil with nitrate produce higher N_2O emissions. In conventional production, the heavy use of fertilizer can lead to excess amounts of nitrate in soils that go unutilized by crops that are frequently off-gassed as N_2O (Hoben et al., 2011). Similarly, soils previously planted to nitrogen-fixing crops such as beans or legume cover crops may increase the amount of total nitrogen in the soil, which can lead to increases in nitrate and potential increases in N_2O emissions (Basche et al., 2014). Optimizing the delivery of nitrogen to crops and ensuring that excess fertilizer is not applied to crops can significantly reduce the potential for N_2O production (Millar et al., 2010).

The primary sources of methane emissions in agriculture are enteric fermentation in livestock, particularly cattle, and methane generation from soils in rice paddy systems. Enteric fermentation is the process by which cattle digest feed in their rumens with the aid of symbiotic microbes, including methanogens. These methanogens are most active in the digestion of complex carbohydrates, meaning cattle fed higher proportions of hay generate more methane. Very recent research has produced a feed supplement that inhibits methane production in the cow's gut, reducing methane production by as much as 30% (Mulhollem, 2015), but reducing emissions in livestock production is generally difficult. Instead, emissions can be offset within the same production systems through the use of rotational grazing practices that increase soil carbon (Machmuller et al., 2015). Perhaps more importantly, reducing or slowing the growth of global livestock production would also reduce the amount of methane produced from agriculture but is contingent on market forces and consumer choices.

Methane emissions are particularly high in the production of paddy rice, which is typically flooded during production. Flooding fields reduces soil oxygen levels, increasing soil methanogen activity, which utilize CO_2 instead of oxygen as a final electron acceptor for metabolic activities. The widespread production of paddy rice and the importance of rice as a staple crop around the world account for the considerable size of rice's GHG footprint. Researchers have recently produced a genetically modified variety of rice that releases fewer carbon compounds into the soil via its roots, thereby reducing the amount of CO_2 that methanogens would utilize (Su et al., 2015). But a simpler approach to reducing methane emissions in rice systems would be to drain fields mid-season when flooding is less necessary for production (Wassmann et al., 1993).

These practices do not lead to direct sequestration of CO_2, but they are important to consider since nitrous oxide and methane represent a large fraction of total GHG emissions from agriculture. Some of these changes could be easily implemented, rapidly reducing agriculture's footprint and shifting agriculture's carbon balance in a more favorable direction.

Converting Land Out of Agriculture

A range of agricultural management strategies have the potential to sequester carbon, but transitioning some land out of agricultural use altogether is an alternative approach. Historic land use conversion of native ecosystems to agriculture is responsible for soil carbon reductions as high as 60-75% (Lal, 2011). Carbon rich ecosystems, such as wetlands (Mitsch et al., 2012) and tropical forests (Dixon et al., 1994) are particularly vulnerable. Simply allowing land to lay fallow in an early successional state after intensive agricultural use can lead to increases in soil carbon (Syswerda et al., 2011), and more aggressive efforts to restore agricultural lands to native ecosystems may yield even better results.

The inherent difficulty with these approaches is that to be implemented, payments or revenue should be greater than the amount that could be earned on said land through agricultural production. Current programs such as USDA's Conservation Reserve Program (CRP) give farmers payments to keep certain marginal areas of their farms out of production and, in some cases, to plant them with flower or prairie seed mixtures. An early study of CRP land found that converting cropland to perennial grass cover in Texas, Kansas, and Nebraska led to increased soil carbon sequestration rates (Gebhart et al., 1994). In addition, USDA's Sodbuster and Sodsaver policies reduce some of the federal incentives to breaking out new cropland. These programs and policies have seen success, but they are also reliant on public funding and/or support and can be overwhelmed by commodity market upswings or perverse federal production subsidies (Stubbs, 2014).

Balancing the need for arable cropland to support a growing global population further complicates this strategy and makes it particularly difficult to estimate its global potential. Nonetheless, converting agricultural land that would otherwise be a high-carbon natural ecosystem, such as wetlands, peat bogs, and tropical forests, may strike that balance by providing an outsized sequestration benefit for the amount of land taken out of production. The same is true of retaining prime grassland in grass-based agriculture rather than converting it to what is often marginal cropland.

Estimated Potential and Knowledge Gaps

Estimates of the global sequestration potential of agricultural soils are typically made for sequestration on an annual basis and range from 0.4 to 1.2 gigatons per year (Gt/yr) (Lal, 2004). Some are more optimistic, including Kell (2011, 2012) who argues that by improving root growth in agricultural crops, soil carbon storage could match anthropogenic emissions for the next 40 years. When multiplied across several years, these rates produce vastly different estimates of the total potential of soil carbon sequestration. An optimistic soil carbon accrual rate could sequester at least 10% of the current annual emissions of 8-10 Gt/yr (Hansen et al., 2013), while a lower rate would account for less than 5%. If deep rooted crops could be elevated and bred, that potential might be even greater.

Rates are generated by estimating the potential carbon sequestration rate in different regions of the world through improved land management and modeling those rates across the estimated agricultural land area available for improvement. A variety of assumptions are inherent in this process, including what types of practices are suited to what regions and an assumption that current models of soil carbon dynamics and saturation are accurate for each region. The majority of estimates are also referred to as technical estimates because they do not consider barriers to adoption and therefore assume a larger scale conversion of land than may be likely (Paustian, 2014). However the estimates may in other cases understate the potential of soil-based carbon sequestration by only looking at existing agricultural land and not to federal, state and private lands where traditional prairies and grasslands might be restored.

Among the most comprehensive attempts at estimating global agricultural GHG mitigation potential is work done by the IPCC working group on mitigation (Smith et al., 2008). It utilizes an extensive database of studies on the carbon sequestration and GHG mitigation potential of a variety of agricultural practices and ecological restoration on currently cultivated organic soils (i.e. wetlands). Smith et al. (2008) estimate a total technical potential of 5500-6000 Mt CO_2-equivalent per year between now and 2030, with 89% of that figure being derived from reduced soil CO_2 emissions. In an additional analysis that priced carbon at different levels to better estimate actual potential, these numbers decreased: 1500-1600 at $20 USD per t CO_2 equivalent, 2500-2700 at $50 USD, and 4000-4300 at $100 USD. These differences are largely driven by varying estimates of the area of organic soils that would be restored at different carbon prices. The highest estimate of Smith et al. (2008) would account for roughly 10% of the current estimated anthropogenic annual carbon emissions of ~8-10 Gt /year (Hansen et al., 2013).

Some researchers have suggested that the IPCC reports are optimistic. Sommer and Bossio (2014) extended estimates beyond 2030 and concluded that since soils might become saturated with carbon, reaching a new equilibrium with the atmosphere, they will cease to be a sink and may only sequester as little as 1.9% of projected emissions. Powlson et al. (2011) suggest that the fact that restoration of organic soils account for such a large proportion of sequestration potential in Smith et al. (2008) is misleading, since there are significant barriers to implementing such restoration efforts.

Still, other researchers argue that the IPCC is too pessimistic. These scientists are optimistic about the technical potential of soils as carbon sinks and their importance in the future. In a response to Sommer and Bossio (2014), Lassaletta and Aguilera (2015) note that the authors diminished the potential of soil carbon sequestration by comparing their estimates of soil carbon sequestration with the most pessimistic of IPCC emissions scenarios and that the next 20-30 years might prove the most crucial period for sequestration efforts by helping to prevent more long-term, negative climate feedback loops such as the release of methane from permafrost upon melting.

Other researchers suggest that sequestration could be significantly increased by increasing the belowground biomass of crop plants to sequester carbon at lower soil depths, which tend to be far from saturated and are protected from disturbance and weather fluctuations that lead to rapid carbon turnover. Kell (2011, 2012) argues that by improving root growth in agricultural crops, soil carbon storage could be greatly enhanced such that it could match anthropogenic emissions for the next 50 years. Such an achievement would however require a substantial plant breeding effort or change in agricultural land use to implement crops with deep roots.

Research Agenda

The broad range of estimates across the literature reflect both a dynamic body of research and differing opinions on the efficacy of implementing different carbon sequestering practices. The full extent of the potential of agricultural soil carbon sequestration may still be unknown, but ample evidence from field trials suggests that sequestering carbon in agricultural soils is possible and can be done in a way that would enhance soils and the ecosystem services they provide. A full accounting of how changing management may lower atmospheric carbon is important, but it should not be considered a prerequisite for action. Instead, the debate should encourage both the environmental and agricultural science communities to push further. Extending research efforts in the following areas may help diminish the research gap and improve estimates of soil carbon sequestration through agriculture in the future.

1.) *Alternative agricultural strategies*

Many of the potential agricultural strategies that would improve carbon sequestration, such as increasing root biomass or creating highly diverse crop rotations, are non-conventional. As a result, they receive comparatively fewer research dollars and attention than more widespread agricultural practices. While continued research on current practices is important, exploring alternative strategies that can sequester carbon and regenerate soils will be essential to truly understanding the capacity of agricultural soils to sequester carbon.

2.) *Soil carbon sequestration dynamics*

While much research has been done on soil carbon and how different practices may increase or decrease it, there are still large knowledge gaps concerning fine-scale dynamics and the interaction of soil carbon with other components of the soil, namely the soil mineral fraction and soil microbial and fungal communities. Additionally, our understanding of how different types of plant-based carbons are processed/sequestered in different soils is similarly limited. Expanding research on these dynamics could better inform our understanding of how different practices and systems will perform on different fields with different soil types, management histories, and climates.

3.) *Improving soil carbon modeling and extending predictions*

Current agronomic and soil models are limited in the number of practices they can accurately model. Most notably, pasture-based systems with intensive management, inter-cropping systems, and relaycropping systems, including those with cover crops sown into standing crops, are difficult to model. Furthermore, while soil carbon modules in these models have tremendous capability, their accuracy could be improved by the inclusion of sub-models that more explicitly identify types of carbon inputs and soil microbial communities. With better models, predictions of how different carbon-sequestering agricultural systems could perform would be greatly improved.

As the science of soil carbon and the numerical models to predict its levels under different management strategies improve, extending predictions to cover larger areas of the managed landscape and comparing scenarios will be important to identifying how best to approach utilizing agricultural soils as a carbon sink. Efforts to estimate the capacity of agricultural soils to act as a carbon sink must be able to consider different geographic, climate, edaphic, and management factors together to be accurate.

4.) *Improved in-field GHG monitoring*

Greenhouse gas emissions from agricultural soils are incredibly variable over time and space. Currently, our tools to measure these emissions are often limited to a series of one-time measurements and are generally incapable of capturing temporal and spatial emissions variability. In addition, while some practices may increase soil carbon, if they simultaneously increase methane emissions (i.e. rotational grazing) their net climate benefit may be limited. Developing better tools for continuous monitoring of soil GHG emissions could close knowledge gaps about how different systems perform in different contexts.

5.) *Developing inexpensive tools*

Most tools for assessing soil carbon and the soil quality benefits it entails are laboratory-based, expensive, and labor-intensive. Developing inexpensive, field-based tools and measurement protocols that are accessible to producers could provide real-time feedback that could help to encourage further adoption of agricultural systems that sequester soil carbon. As models improve and as farmer-friendly field tools are developed, carbon sequestration and soil health more broadly could become a far greater focus of federal and state conservation technical and financial assistance programs than is currently the case.

6.) *Economic research to understand barriers to adoption and how to overcome them*

Although there is a significant body of research documenting the improvements certain practices can make to soil carbon and soil quality overall, adoption rates amongst producers remain low because of economic and social barriers and an absence of policies to encourage their adoption. Understanding how farmers make decisions and what policy tools and financial incentives encourage sustained adoption could help to inform decisions made by policymakers, local agencies, and advocacy groups.

Conclusions

Soil carbon sequestration involves transferring atmospheric carbon into the soil via plant photosynthesis and keeping those soil-based carbon pools protected as effectively as possible from microbial activity that will release the carbon back to the air. There are agricultural management practices that show promise for restoring soils and sequestering a very significant portion of atmospheric carbon. The need for drawdown strategies is increasingly urgent and soil carbon sequestration through agriculture warrants far greater attention from policymakers, climate negotiators, farmers, ranchers, and scientists. Most, if not all, of the management regimes that promote carbon sequestration also improve soil aggregation, water retention, soil fertility, and food security. These important co-benefits should serve as motivation for increased action.

Considerable debate over the potential of soil carbon sequestration remains and will continue to remain in the near future. Soil carbon cycles and protection dynamics are still not fully understood in all locations of the world, and variable patterns of land ownership/management and market forces make it difficult to predict the adoption of agricultural or land management practices that can sequester carbon. Nonetheless, a complete understanding of soil carbon and the sequestration potential should not be a prerequisite for action.

Extensive research on a variety of different agricultural and land management practices has produced a number of candidate strategies for increasing the amount of carbon that is stored in soils. Compared to a number of other atmospheric drawdown solutions, these practices are relatively cheap, low-risk, and could be implemented in the near future. The risks are minimal while the known co-benefits of improving soil quality are numerous. The potential for carbon sequestration relies on early adopters and policies to promote a change in practices. Public policies intended to address climate change should consider soil carbon sequestration more seriously as a candidate practice for drawdown.

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The **National Sustainable Agriculture Coalition (NSAC)** is an alliance of grassroots organizations that advocates for federal policy reform to advance the sustainability of agriculture, food systems, natural resources, and rural communities. NSAC's vision of agriculture is one where a safe, nutritious, ample, and affordable food supply is produced by a legion of family farmers who make a decent living pursuing their trade, while protecting the environment, and contributing to the strength and stability of their communities. *http://sustainableagriculture.net*