Combatting Climate Change on US Cropland: Affirming the Technical Capacity of Cover Cropping and No-Till to Sequester Carbon and Reduce Greenhouse Gas Emissions

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Contents

Introduction

Outline

Globally, soils store two to three times more carbon than the atmosphere and up to four times the amount of carbon stored in the vegetation on land (Lal, 2018; IPCC, 2013). How we manage these carbon stocks has a significant impact on climate change (Stockmann et al., 2013). Since the advent of modern agriculture, we have lost more than half of the organic carbon originally stored in U.S. soils (Lal, 2004). With nearly 400 million acres of cropland in the U.S., the country has an enormous opportunity to rebuild soil organic carbon (SOC), sequester atmospheric carbon, and reduce greenhouse gas (GHG) emissions.

This report focuses on the significant potential of no-till and cover crop practices to increase soil carbon sequestration and reduce nitrous oxide (N_2O) emissions for a net reduction in GHG emissions. Although there is still much to learn about SOC sequestration, the existing literature is nonetheless clear that regenerative practices do sequester carbon and could prove useful in combatting climate change. These practices are relatively cost-effective and rely on current technology and knowledge, making them available for immediate implementation (Fargione et al., 2018; Paustian et al., 2016; Paustian et al., 2019a; 2019b). Furthermore, there are significant acres available in the U.S. for implementation of these practices. As of 2017, there are about 178 million acres of U.S. cropland available for conversion to no-till (80 and 98 million in intensive and reduced till, respectively), while over 250 million annual row-crop acres are available for cover crop planting (USDA-NASS, 2017). This report summarizes the current state of the science surrounding these practices and their impact on SOC and GHG emissions, including important limitations of our current understanding. Additionally, we outline an ambitious yet feasible path toward harnessing the sequestration potential of U.S. soils.

Quick Primer on US Agricultural Emissions

The U.S. conducts a national, annual inventory of GHG emissions and sinks (EPA, 2020). The major GHG emission sources quantified include electricity, transportation, industry, commercial/residential, agriculture, and land use/forestry. The U.S. agriculture sector produced 618.5 million metric tons (MMT) of CO_2 equivalents (CO_2e) in 2018, or 9.3% of the total U.S. GHG emissions. In contrast to other sectors where most of the GHG emissions are related to CO_2, most of the agricultural emissions are related to N_2O emissions from agricultural soil management. Approximately 55% of total agricultural GHG emissions, or 338 MMT CO_2e, are due to N_2O from practices that increase soil nitrogen levels, such as fertilization, manuring, and growing legumes. Enteric fermentation by ruminant livestock and manure management account for an additional 42% of agricultural emissions, mainly as methane. However, this document focuses on two regenerative agricultural practices, such as cover cropping and no-till, which sequester carbon in cropland soils and reduce N_2O emissions. The reader is referred to Rojas-Downing et al. (2017) and Gerber et al. (2013) for a review of climate change impacts and mitigation potential from livestock systems.

The Role of Soils

Restoring lost SOC in our agronomic systems through soil health management or regenerative agriculture practices holds significant promise in the quest to combat climate change (Paustian et al., 2019b). Since the advent of modern agriculture, we have lost more than half of the organic carbon originally stored in U.S. soils (Lal, 2004). Major factors for SOC loss include the historic conversion of forest and grasslands to agronomic use, erosion, and severe land degradation (Lal, 2018). Increasing SOC sequestration can rebuild soil C stocks back toward the level under native vegetation, but it will be difficult or impossible to fully rebuild soil C in croplands. Given that the SOC pool is up to four times the amount of carbon stored in the vegetation on land, small changes to the SOC pool have major impacts on the global carbon budget (Stockmann et al., 2013). For instance, SOC pools are increased by drawing carbon out of the atmosphere and storing it below ground, while increased temperatures could result in loss of CO_2 to the atmosphere through accelerated decomposition rates (Lal, 2020). Rebuilding soil health is crucial to sustain agriculture, enhance the profitability of farmers and ranchers, and combat the impacts of climate change. Some estimates suggest that if the U.S. were able to adequately address economic, social, and technical barriers to implementing all viable soil-based carbon mitigation practices, U.S. croplands have the potential to mitigate 140-371 MMT CO_2e per year (Smith et al. 2008, Eagle et al. 2012, Chambers et al. 2016, Fargione et al. 2018, Sperow et al. 2020).

Soil carbon sequestration begins with plants capturing CO_2, through photosynthesis, and converting it to organic carbon compounds in plant tissues. Carbon is then cycled into the soil through root exudates (i.e., carbon-rich compounds that “leak” from plant roots to stimulate soil microbes) and through decomposition as plants die and are decomposed by soil organisms. Most of the carbon is released to the atmosphere as CO_2 during decomposition, but some of this carbon is stored in the soil. When the stored carbon is protected from physical degradation or microbial attack, the carbon is stored long term or sequestered.

The rate that carbon can be sequestered or lost from the system is driven by the interplay between farming practices and the underlying physical and environmental conditions of an area. Some of these drivers—including soil texture, climate, and topography—are inherent to the system and can not be easily changed, while others—including how much carbon is returned to the system and how that carbon is protected—can be influenced by field-scale management (Figure 1). It is well established that intensive tillage has reduced SOC levels relative to pre-cultivation levels, and that no-till and cover cropping can increase soil carbon levels and overall soil health and ecosystem function (Blanco-Canqui et al., 2015; Paustian et al., 2019b; Poeplau and Don, 2015). Cover crops and no-till have been successfully implemented in multiple cropping systems across the U.S. and are relatively inexpensive. Moreover, cover crops and no-till help protect soil from the erosive forces of wind and water by covering the soil with living plant cover or crop residues remaining on the surface. In addition to the recognized benefits to water quality, reducing erosion also has significant impacts on reducing CO_2 emissions as eroded soil particles (which contain substantial amounts of soil organic matter) are subjected to accelerated transformation to CO_2. By one estimate, approximately 4 billion tonnes of CO_2e are lost per year on a global basis due to erosion (Lal, 2018).

The potential of SOC sequestration is not infinite, as each soil has a maximum capacity (Stewart et al., 2007). According to Lal (2004), following adoption of key practices such as cover cropping and no-till, the rate of carbon sequestration tends to be more rapid initially, with further increases slowing over time. Depending upon the system, region, soil, and climate conditions, a new maximum equilibrium can be achieved within 10 to 50 years as a result of using practices such as no-till and cover cropping. Once this new maximum equilibrium has been achieved, practices must be maintained, and the land must not be disturbed in a way that will re-release carbon into the atmosphere, including through tilling or converting farmland for other uses.

Comparing Apples to Apples: Converting Between Carbon and Carbon Dioxide Equivalents

Values in this report are expressed as carbon dioxide equivalents (CO_2e) and reported in metric ton (tonne) increments.

Carbon dioxide equivalents are a global warming potential weighting of emissions, based on radiative forcing over a 100-year time scale, resulting from the release of 1 kg of a substance as compared to 1 kg of CO_2 (IPCC, 2013). In most models for agricultural systems, the three main GHGs reported for each conservation practice are CO_2, N_2O, and CH_4 (methane). Carbon dioxide has a global warming potential of 1 and is used as the reference. Nitrous oxide has a global warming potential of 298 and CH_4 a global warming potential of 25 (EPA, 2020).

In this report, we focus primarily on the impact of cover cropping and no-till practices on carbon sequestration and N_2O emissions, and when appropriate, report the results in net CO_2e reductions. Except for rice production, most agronomic soils are aerobic and serve as a net sink for CH_4, and thus, are not included in most studies. Sometimes, researchers only focus on carbon sequestration and will report the amount in tonnes of C instead of CO_2. To convert from C to CO_2e, multiply by 3.67, which is the ratio of the molecular weight of CO_2 to the molecular weight of carbon or 44:12. For ease of interpretation, all numbers reported in this document have been converted using this multiplier.

Summarizing the Science

Cover Crops

Practice Introduction

Cover crops typically are grown in the "off season," such as over the winter following fall harvest, during the summer in winter wheat systems, or in one-to-two-month windows between short-lived vegetable crops. Cover crops typically are not harvested to produce a marketable yield of seeds or fruits but may be grazed or harvested for forage.
Cover crops have been used for hundreds of years to improve soil fertility and provide numerous other ecosystem services and on-farm co-benefits, including erosion control, water quality regulation, soil moisture retention, nutrient management, and weed and pest control, among others (Daryanto et al., 2018). More recently, cover crops have been identified as a potential tool for building SOC and thereby removing CO_2 from the atmosphere (Poeplau and Don, 2015; Kaye and Quemada, 2017).

Cover crops can sequester carbon in a few ways. First, they increase total annual plant growth by their presence when the field would otherwise be bare, which adds carbon to the soil system. Second, cover crop roots and residues promote abundant and diverse soil microbial communities. When these microbes die, their bodies break down into C-rich compounds that adhere to soil particles (e.g., silt, clay). The combination of active roots and sticky microbial compounds hold the soil together in small clumps called aggregates, which are resistant to disturbance by wind, rain, and tillage. This helps protect soil carbon so that it stays in the soil, rather than being lost back into the atmosphere as CO_2.

Cover crops are a promising tool for sequestering carbon in agricultural soils because they do not displace cash crops from the field and can even enhance cash crop yields (Marcillo and Miguez, 2017). That said, there are substantial barriers associated with cover cropping, which have been comprehensively summarized elsewhere (Roesch-McNally et al., 2018, see Overcoming Barriers Section of this Report). Other practices that extend the growing season, such as double cropping and perennials, can provide similar or greater C sequestration benefits but are outside the scope of this report.

State of the Science

Several reviews and meta-analyses have demonstrated significant SOC increases attributable to the use of cover crops (Abdalla et al., 2019; Poeplau and Don, 2015; Ruis and Blanco-Canqui, 2017). For instance, an analysis of 20 paired long-term experiments reported a sequestration rate of 0.40-0.64 MMT CO_2e per acre per year (Bollinder et al., 2020). A separate analysis of 131 controlled comparison studies with and without cover crops reported a mean increase in SOC of 0.83 MMT CO_2e per acre per year attributable to cover crops (Jian et al., 2020). However, factors such as the number of sequential years planting a cover crop, how long the cover crop is grown before termination, and cover crop species can affect the magnitude and direction (positive and negative) of SOC change (Blanco-Canqui and Jasa, 2019). One review found that the largest SOC increases are associated with temperate locations, fine-textured soils, and mixed species plantings of cover crops (Jian et al., 2020).

Recent studies have begun to look at the effects of cover crops on soil C stocks at deeper soil layers (below 12 inch depth) and throughout the whole profile. These studies have shown that the management context in which cover crops are grown—such as nutrient applications and tillage—influences whole-profile SOC accrual. For instance, in a long-term maize-tomato and wheat-fallow study in California, Tautges et al. (2019) determined that winter cover crops alone resulted in a loss of SOC compared to baseline conditions, when considering the whole soil profile (6.5 feet). However, winter cover crops combined with manure inputs increased SOC by about 13% over the whole profile. The authors propose that SOC loss at depth without manure may have been due to inadequate nutrient supply, which is known to influence carbon sequestration, especially at depth (Frossard et al., 2016). Kirkby et al. (2016) also found SOC increased down to 5 feet when supplemental nutrients were added along with crop residues, but SOC declined if the same amount of crop residues were added without nutrients. These findings suggest that proper cropping system management is required to maximize the SOC sequestration benefit of cover crops, especially at depth.

In addition to SOC sequestration and prevention of carbon losses due to erosion, cover crops also have been found to reduce N_2O emissions. By scavenging surplus soil nitrogen, cover crops resulted in a fivefold reduction of N_2O emissions in Illinois (Behnke and Villamil, 2019). In contrast, other research has indicated a net release of N_2O from cover crops (Mitchell et al., 2013) or no significant effects (Abdalla et al., 2019). Management decisions such as type of cover crop (i.e., legume vs. non-legume species), residue management following cover crop termination, and fertilization rates of the subsequent cash crop are key drivers in whether soils are a net source of N_2O with cover crops (Basche et al., 2014). In a meta review, Basche et al. (2014) determined that N_2O emissions were reduced when non-legume species were planted relative to legume species. However, when N_2O emissions were measured across the entire year, cover crops had negligible effects on N_2O emissions. Additionally, Basche et al. (2014) found cover crop residue incorporation through tillage increased N_2O emissions, an important finding that demonstrates the increased climate mitigation potential of cover crops and no-till when implemented together.

Altogether, these results indicated that the inclusion of cover crops into agricultural rotations increases SOC sequestration potential, reduces surplus nitrogen, improves many soil health parameters, and serves as a potential sink for atmospheric CO_2. Cover crops could theoretically be adopted on over 250 million acres devoted to annual row crop production in the U.S., making the potential GHG reduction quite high.

No-till

Practice Introduction

No-till is a system of establishing annual crops without disturbing the soil (i.e., tillage) prior to planting. Under conventional tillage, farmers prepare soil for planting by mixing and smoothing the top layer of the soil with a plow and/or other tractor-drawn implements. This incorporates any surface residues or manures into the soil and helps prepare a uniform seedbed that enables successful germination. However, plowing also causes soil compaction and leaves soil bare and vulnerable to erosion. No-till practices avoid these damaging steps by planting directly into soil that has not been disturbed since the last crop was harvested. Specialized no-till planting equipment can achieve good germination despite only disturbing a small portion of the field (the seed slot). After a short transition period, no-till can produce similar crop yields to conventional tillage in many areas and cropping systems (Pittelkow et al., 2015). No-till also requires fewer tractor passes across the field, which reduces labor, fuel costs, tractor emissions, and compaction due to wheel traffic.

No-till practices can sequester SOC by greatly reducing soil disturbance. Tillage breaks up the soil aggregates that protect soil carbon, which exposes the carbon compounds to microbial breakdown and results in loss of carbon to the atmosphere as CO_2 (Six et al., 1999). In contrast, no-till maintains and improves soil aggregation, creating an environment where SOC can build up and remain stable for many years. Primary mechanisms thought to contribute to reduced losses and increased storage of SOC under no-till have been described previously (Six et al., 2004, 2002), though our understanding of soil organic matter pools and fluxes, and the microbial communities that drive these processes is evolving rapidly (Lehmann and Kleber, 2015).

Soil carbon accumulation is most pronounced in the surface layer of soils managed with no-till, since this is where organic carbon inputs from crop roots and residues are most concentrated. Since crop residues are not distributed throughout the plow layer in no-till as they are in conventional tillage, SOC can decline below ~8-12 inch depth. There is debate, summarized below, about whether this decline offsets the benefits of the surface SOC accumulation. Overall, evidence suggests that there is substantial potential for whole-profile SOC accumulation in large areas of the U.S.

No-till and conventional tillage are two ends of a tillage spectrum that also includes many other systems with more soil disturbance than no-till, but less disturbance than conventional tillage. One important example is strip-till, in which most of the soil surface is left undisturbed, but a narrow strip—roughly 8-10 inches wide where the seed is planted—is shallowly disturbed. This practice can aid in warming the soil in the spring, allowing earlier planting and higher yields, while retaining most of the conservation benefits of no-till, including SOC accumulation (Al-Kaisi and Kwaw-Mensah, 2020). NRCS includes no-till and strip-till under the same practice standard (329).

State of the Science

No-till management has been promoted as a low-cost practice to mitigate GHG emissions for multiple decades (Paustian et al., 1997; Sperow, 2019). Several factors affect the magnitude of SOC sequestered under no-till, including soil type, landscape position, climate, crop rotation and practice duration, among others (Liang et al., 2020; Ogle et al., 2019, 2005). Significant increases in SOC content of surface soils (0-12 inch depth) under no-till compared to conventionally tilled soils have been well documented (Bai et al., 2019; Franzluebbers, 2010; Ogle et al., 2005; Powlson et al., 2014; Smith et al., 2008; West and Post, 2002). However, meta-analyses investigating SOC stock changes in deeper soil layers have reported mixed results, calling into question the ability of no-till to sequester SOC throughout the entire depth of the soil profile (Powlson et al., 2014).

Early research into the depth distribution of carbon stock changes attributable to no-till suggested that significant carbon accrual may be limited to the surface soils with higher SOC concentrations under conventionally tilled systems at lower depths (Baker et al., 2007). Subsequent analyses have yielded inconsistent results, with some showing that whole-profile SOC accumulation is still higher under no-till (Angers and Eriksen-Hamel, 2008) and others showing that conventionally tilled systems have equivalent SOC (Luo et al., 2010; Powlson, 2014). Possible explanations for inconsistent results from previous meta-analyses of whole-profile carbon stocks include discrepancies in statistical analyses, soil sampling strategies, and analytical approaches to SOC determination, among others (Huang et al., 2020a; Kravchenko and Robertson, 2011; Syswerda et al., 2011). Global efforts are under way to enhance quantification protocols to help resolve this inconsistency (Paustian et al., 2019a; Smith et al., 2020).

Despite these critiques, recent analyses suggest that there are several geographies that offer substantial opportunity for significant SOC gains under no-till throughout the whole profile. Sun et al. (2020) paired yield data from Pittelkow et al. (2015) with a meta-analysis of 115 published studies comparing SOC stock changes in no-till vs. conventionally tilled soils. Their research found significant SOC gains with no changes in yield in regions with a humidity index between 40 and 100, including most Midwest and Eastern U.S. cropland soils. Furthermore, a subset of the data revealed overall SOC gains in no-till soils compared to conventional till to a 40-inch depth. These results agree with Ogle et al., 2019 whose meta-analysis of 178 studies showed significant SOC gains in a variety of soils across temperature and moisture regimes found in the Midwest and Eastern U.S. across multiple sampling depth intervals down to 24 inches. Most U.S. cropland soils are in temperature and moisture regimes ideal for increasing carbon gains from adoption of no-till, and there is persuasive evidence to support the continued promotion of this practice for carbon sequestration in these regions (Liang et al., 2020; Sperow, 2020; Sun et al., 2020). In summary, scientific evidence suggests that conversion from conventional tillage to no-till systems increases SOC storage and sequestration and reduces carbon losses from erosion. With roughly 178 million acres available for no-till implementation in the U.S., the potential GHG reduction of increased no-till adoption is substantial.

Overcoming Barriers

Successful implementation and widespread adoption of cover crops and no-till at the scale required to significantly sequester carbon and reduce GHG emissions necessitates strategies that take regional cropping systems, soil conditions, cultural norms, and local economies into consideration (Prokopy et al., 2019; Ranjan et al., 2019). Recognizing that each farm is unique and that no single solution applies to all situations, there are commonalities among the barriers and strategies to address them that are summarized here.

Technical and financial barriers – There is a learning curve associated with adopting new practices, requiring adaptation of planning and management activities, and often necessitating access to new equipment and increased upfront costs. Most farmers operate on tight margins, with little ability to spend money on practices that may not offer a large initial return on investment. Cover crop and no-till adoption can present extra challenges in certain climates and cropping systems, especially in cold areas with long-season annual crops or in areas with limited soil moisture. The potential for decreased yields while experimenting with cover crops and transitioning to no-till presents additional financial risks.

Solution strategies:

- Address technical barriers by providing training and resources to support farmers learning how to transition to a new practice. On-farm demonstrations and peer-to-peer information have proven effective in knowledge transfer (Prokopy et al. 2019).
- Employ novel methods of cover crop planting and termination that ensure successful establishment and adequate growth, and thus can significantly accelerate the experienced benefits of this practice and extend the planting window for cover crops in colder climates (Duiker, 2015).
- Utilize cover crop mixes incorporating legumes that have been shown to increase yields in multiple meta-analyses (Abdalla et al., 2019; Marcillo and Miguez, 2017) and could help ameliorate yield concerns (Myers et al., 2019).
- Adopt strip-till farming, which may be a viable alternative to no-till for some cropping systems more susceptible to yield losses. Recent work across multiple sites and tillage treatments in Iowa suggests C gains from strip tillage are comparable to gains achieved via no-till (Al-Kaisi and Kwaw-Mensah, 2020).
- Use incentives to help farmers buffer financial risks associated with experimenting with new practices, ideally for 3-5 years until soil health benefits are realized and farmers have had adequate time to become accustomed to management changes.

Social and structural barriers – Farmers’ willingness to adopt cover crops and no-till can be negatively impacted if these practices fall outside of local social norms associated with the region or the predominant cropping system: for example, a perception that a “clean” field is the sign of a good farmer. Further, it can be difficult to employ new practices if their success relies on larger system-level changes. For instance, one structural barrier to getting conservation on farmland is the high rate of rented lands, which in parts of the U.S. are greater than 80%, with an average of about 40% for all US farmland (Bigelow et al. 2016).

Solution strategies:

- Create robust social networks for farmers to learn from one another, experiment with new practices, and/or observe others who are experimenting (Carolan 2006; Coughenour, 2003). These networks are most effective when they are farmer-driven and use participatory methods (Hassanein 2000).
- Harness the interest of non-operating landowners in supporting their tenants' implementation of additional conservation practices by modifying lease structures, particularly as it relates to risk sharing when it comes to experimenting with new practices (Petrzelka et al. 2020).
- Support farmers in taking a holistic approach to incorporating a new practice that might force them to make other changes to their operation (e.g., cover crops might change the timing of an entire cropping system plan) and facilitate their learning from other farmers (Basche and Roesch-McNally 2017; Ranjan et al. 2019).

What Do the Models Tell Us?

Estimates of GHG Reduction Potential of No-till and Cover Crops

Detecting changes in SOC can take many years to decades due to measurement challenges caused by high spatial variability in SOC stocks (Smith, 2004). Furthermore, measurement of GHGs requires expensive equipment and technical expertise, limiting our ability to collect data with the spatial and temporal resolution necessary to inform policies and programs at a national or global scale. Thus, scientists rely on models to predict changes in SOC and GHG emissions under different scenarios to estimate the biophysical capacity of agricultural soils to mitigate climate change and reduce emissions. Some authors have used these models to estimate agriculture's total technical potential by assuming nearly complete adoption of cropland and grazing land management practices known to sequester carbon and reduce N_2O emissions. Estimates suggest that if the U.S. were able to adequately address economic, social, and technical barriers to implementing all viable soil-based carbon mitigation practices, U.S. croplands have the potential to mitigate 140-347 MMT CO_2e per year (Smith et al. 2008, Eagle et al. 2012, Chambers et al. 2016, Fargione et al. 2018, Sperow et al. 2020). Variability within this range is due to several factors, including the land area considered, the practices accounted for, and the assumed efficiency of those practices. In general, these estimates are based on changes in agricultural practices, not the absolute physical potential if soils were managed solely for carbon mitigation (e.g., by restoring native prairies or forests).

Some studies also provide specific estimates of the mitigation potential of cover crops and no-till (when applied individually). Total potential mitigation from cover crops has been estimated to range from 65-188 MMT CO_2e per year (Eagle et al. 2012, Fargione et al. 2018, Sperow et al. 2020). This wide range is due to a combination of highly variable estimates of available land area (131-245 million acres) and of mitigation rates (0.47 – 0.77 Tonnes CO_2e per acre per year). Estimates of the total mitigation potential from adoption of no-till also vary widely from 68-138 MMT CO_2e per year (Eagle et al. 2012, Sperow et al. 2020), largely due to variation in mitigation rates (~0.33-0.60 Tonnes CO_2e per acre per year), as these studies assumed similar levels of available land area (~204-232 million acres). Assuming the climate benefits for each practice are additive, combining cover crops and no-till could result in a total CO_2e reduction potential of 133-326 MMT annually. This range represents 21.5% to 52% of 2018 U.S. agricultural emissions (EPA, 2020). As explained in the next section, combining these practices may have a synergistic impact. Furthermore, increased benefits are expected with implementation of additional management practices across the landscape (Fargione et al. 2018, Sperow et al. 2020).

Synergies from a Systems Approach

Classic experimental designs for agronomic studies tend to control for as many variables as possible to explore the specific impact of a single practice. This approach has the advantage of isolating key drivers of independent practices but fails to address the potential synergies that a more integrated systems-approach can provide (Lal, 2015). Studies investigating the benefits of combining no-till and cover cropping are limited. The few that have explored the synergies have reported enhanced soil physical and chemical effects, including increased carbon sequestration (Blanco-Canqui et al., 2015, 2011; Olson et al., 2014). For example, relative to baseline conditions, SOC sequestration occurred in the top 75 cm (2.5 feet) of the soil profile when cover crops were included, regardless of tillage practice, with the most pronounced effects in the no-till system compared to chisel plow or moldboard plow (Olson et al., 2014). In this study, the hairy vetch and cereal rye cover crop sequestered 1.3 tonnes CO_2e ac^{-1} y^{-1} under no-till, 0.7 tonnes CO_2e ac^{-1} y^{-1} under chisel plow, and only 0.1 tonnes CO_2e ac^{-1} y^{-1} under moldboard plow compared to systems without cover crops after 12 years of management.

Model simulations and other field studies support these findings and suggest that no-till and cover crops work synergistically to increase SOC, with most of the carbon accruals attributed to the cover crop addition and protection of SOC losses with no-till practices (Huang et al., 2020b). In one study covering the Midwest corn belt, CO_2e ac^{-1} y^{-1} was estimated under modeled and field-validated sites with the combined practices of no-till, cereal rye cover crop, and spring applications of nitrogen fertilizer (McNunn et al., 2020). Relative to a cropping system with no cover, conventional tillage, and fall applied nitrogen, the no-till/cover crop/spring nitrogen system resulted in a net reduction of CO_2e of 1.1 tonnes ac^{-1} y^{-1}.

The Path Forward

Our Approach

We can estimate the net amount of CO_2e reduced from implementation of various cropland management practices using the Carbon Reduction Potential Evaluation (CaRPE) Tool (https://carpe.shinyapps.io/CarpeTool/). The CaRPE Tool was designed by American Farmland Trust in collaboration with the USDA-ARS to quantify and visualize county-level net CO_2e reductions resulting from the implementation of a variety of cropland and grazing land management practices. The CaRPE Tool scales the emission reduction coefficients (ERCs) extracted from the COMET-Planner tool to the county level by coupling the coefficients with cropland acres from the 2017 Census of Agriculture (USDA-NASS, 2017). The ERCs are expressed as the tonnes of CO_2e reduction potential per acre per year and reflect the net effect of practice implementation on GHG emissions (mainly N_2O) and carbon sequestration relative to baseline conditions. Assessments using COMET-Planner are designed to be appropriate for multi-county to regional planning purposes based on the combined spatial and temporal metamodeling approach of COMET-Farm. All reported values and climate benefits in this report are estimated values and should be used for general planning purposes only. It is assumed that once a practice is implemented, it remains in place to realize its full potential. As explained by Swan et al. (2019), baseline scenarios represent current management practices typical to the region and assume minimal use of conservation management practices.

Model Introduction

The DayCent Model is used to estimate N_2O and CH_4 emissions from agricultural soils for the EPA US National Greenhouse Gas Inventory (US-EPA, 2020). Based on the process-based, biogeochemical model called Century, DayCent simulates fluxes of carbon and nitrogen between the atmosphere, vegetation, and soil at a daily time step (Delgrosso et al., 2005; Parton et al., 1998). DayCent consists of sub-models for soil water content and temperature by layer, plant production and allocation of net primary production, decomposition of litter and soil organic matter (SOM), mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH_4 oxidation in unsaturated soils.

COMET-Farm and COMET-Planner were developed by scientists at Colorado State University in collaboration with USDA Natural Resources Conservation Service (NRCS). COMET-Farm is the official GHG quantification tool of the United States Department of Agriculture. It uses algorithms from DayCent and up to 35 other models to estimate SOC stock changes and GHG emissions under "what if" management scenarios. COMET-Planner utilizes the meta-modeling approach of COMET-Farm to produce generalized estimates for 35 conservation practice standards recognized by the NRCS.

Using CaRPE, we estimated the total technical potential for CO_2e reduction from adoption of cover crops and no-till. We found that cover crops implemented on roughly 261 million acres of all harvested cropland (excluding hayland and other grasses) could reduce CO_2e emissions by about 88 MMT CO_2e. Additionally, if all tillable acres (approximately 281 million acres) implemented no-till/strip-till practices, another 158 MMT CO_2e could be reduced relative to current use of intensive or reduced till. These estimates include CO_2e reductions provided by acres currently in cover crop, no-till, and reduced till practices. Summing both practices, the CO_2e reduction potential is 246 MMT annually, which could equate to a CO_2e reduction equal to 40% of 2018 U.S. agricultural emissions. This amount is equivalent to the GHG emissions from 53 million passenger cars driven for one year. These estimates are in line with the range of technical potential for CO_2e reductions from these practices on U.S. cropland (Sperow et al., 2020; Eagle et al., 2012). However, the potential theoretical benefit is limited by the fact that universal adoption is not feasible. To showcase what is practical at this time, we have developed an achievable scenario that acknowledges the barriers summarized above .

An Achievable Scenario

This scenario involves implementing cover crops on an additional 15% of cropland acres and converting 25% of current acres in intensive and reduced tillage to no-till. This scenario is not intended to be prescriptive, but moreso an attempt at identifying major areas where implementation could be successful.

We selected states with optimum temperature and moisture regimes for cover crops and no-till implementation as identified by recent studies (Table 1) (McNunn et al., 2020; Ogle et al., 2019; Sperow, 2020; Sun et al., 2020). Briefly, we included the same corn belt states as McNunn et al. (2020) with the addition of Wisconsin and all the southeast states apart from Florida, due to different cropping systems and climate regimes found in this state. We fully acknowledge that these and other practices offer similar benefits in regions outside of those selected for this report.

The selected area included 12 states from the corn belt (ND, SD, NE, KS, MN, IA, MO, IL, IN, MI, OH, and WI) and 11 states from the southeast (AL, AR, GA, KY, LA, MS, NC, SC, TN, VA, and WV). These states tended to have the highest state-weighted emission reduction coefficient for adopting a legume cover (Figure 1), non-legume cover (Figure 2), and no-till (Figure 3) management. Furthermore, they also tend to have appreciable cropland acres (Figure 4) and occur in an area where precipitation would not limit establishment of the covers. Tables 2 and 3 summarize total acres adopting suggested practices (including current and future adoption), weighted ERCs for each stage of implementation, total CO_2e reductions and notes for each scenario. Emission reductions from current practice implementation were calculated based on current acres in production (USDA-NASS, 2017) and are not uniformly distributed across the states. Implementation of practices on new acres was proportionately distributed across all selected states, such that ERCs are not constant when comparing between current and future estimates (Tables 2 and 3). State-wide variation in weighted ERCs is reflected in Figures 2-4.

In the corn belt and southeastern states described above, cover crops had been implemented on approximately 11 million acres as of 2017, representing about 73% of total U.S. cover crop adoption (USDA-NASS, 2017). Cereal rye is one of the most common cover crop species used in the U.S. (CTIC, ASTA and SARE, 2020), with some farmers beginning to plant legumes. Thus, for our scenario we assumed 75% of the 11 million acres in cover crops had been planted with a non-legume cover and 25% had a legume cover. This translates to a reduction of about 4.3 MMT CO_2e per year compared to the baseline practice of no cover crop.

To estimate the impacts of additional acres implementing cover crops, we ran a scenario where 15% of the 232 million acres available for cover crops implemented covers with the same 75:25 non-legume: legume ratio as described above. The "available" acres for cover crops were estimated as cropland acres not in hayland production or currently in cover crops. Acres under fallow or idle status also were excluded. Under this scenario, an additional 35 million acres implemented cover crops (for a total adoption level of 20%), which resulted in an additional reduction of 11.9 MMT CO_2e per year. In total, cover crop adoption occurred on approximately 20% of the available U.S. cropland acres, for a total CO_2e reduction of 16.1 MMT CO_2e per year (Figure 5). This is equivalent to the GHG emissions from 3.5 million passenger vehicles driven for one year or the amount of carbon sequestered by 266 million tree seedlings grown for 10 years.

In the selected states, currently there are 82 million, 79 million, and 56 million acres in no-till, reduced till, and intensive till, respectively. Assuming current no-till and reduced till acres started in intensive tillage, total no-till and reduced till acres have been reducing about 63 MMT CO_2e per year. If we convert 25% each of current intensive till and reduced till acres to no-till or strip till—a total of 34 million acres—an additional 17.7 MMT CO_2e could be reduced annually. The sum of current and future potential under this scenario results in a total of 81 MMT CO_2e reduced each year, an amount equivalent to the GHG emissions from 17.5 million passenger cars driven for one year or the amount of carbon sequestered by 1.3 billion tree seedlings grown for 10 years.

Summary

Overall, no-till and cover crop practices aid in combatting climate change by increasing the amount of SOC that is formed, protected, and ultimately sequestered in soil. Ideally, for optimal synergistic impacts, practices should be combined into comprehensive soil health management systems that are also designed to address nutrient, water, and pest management. Recognizing the many barriers and limitations to immediate and widespread adoption, we provided an achievable scenario to increase adoption of these practices for the specific goal of sequestering carbon and reducing net CO_2e emissions. The targeted area represents states where 75% of national cover crop acres already were in place and where no-till exists on 38% of 2017 reported tillable acres. Thus, successful implementation exists and can be leveraged throughout the region to expand adoption. Through maintenance of current cropland acres under no-till and cover crops, and new implementation of cover crops on 35 million additional acres and no-

till on another 34 million additional acres, up to 97 MMT CO_2e per year could be reduced relative to baseline management.
The estimated CO_2e reduction potential from the scenario developed for this report is conservative given how the ERCs used in this report compare to those reported in other studies on U.S. agricultural lands (Table 1). Additionally, several studies point to higher SOC sequestration estimates from investigations of cover crops established over longer periods and in systems where farmers manage for maximum biomass production once cover crops are established (Ruis and Blanco-Canqui, 2017; Tellatin and Myers, 2018).

Current soil management on U.S. cropland has contributed to restoring SOC, but the opportunities to expand adoption are substantial. By harnessing the synergistic benefits of simultaneous practice adoption and proper whole system long-term management, U.S. soils have the capacity to aid in reversing climate change. Although this report focused on only two practices, the opportunities do not end with the practices discussed here. Future reports will add to this body of knowledge to help promote additional cropland and grazing land practices. We urge technical, financial, and social support of our farmers and ranchers; financial and programmatic support for the scientific community in researching and improving models and mechanistic understanding; and increasing capacity for NRCS and local Soil and Water Conservation District field staff.

Figure 1. Diagram depicting a basic soil carbon cycle. When the amount of organic carbon added to the soil is protected and exceeds the amount that is lost, soil organic matter increases, leading to long-term carbon sequestration.

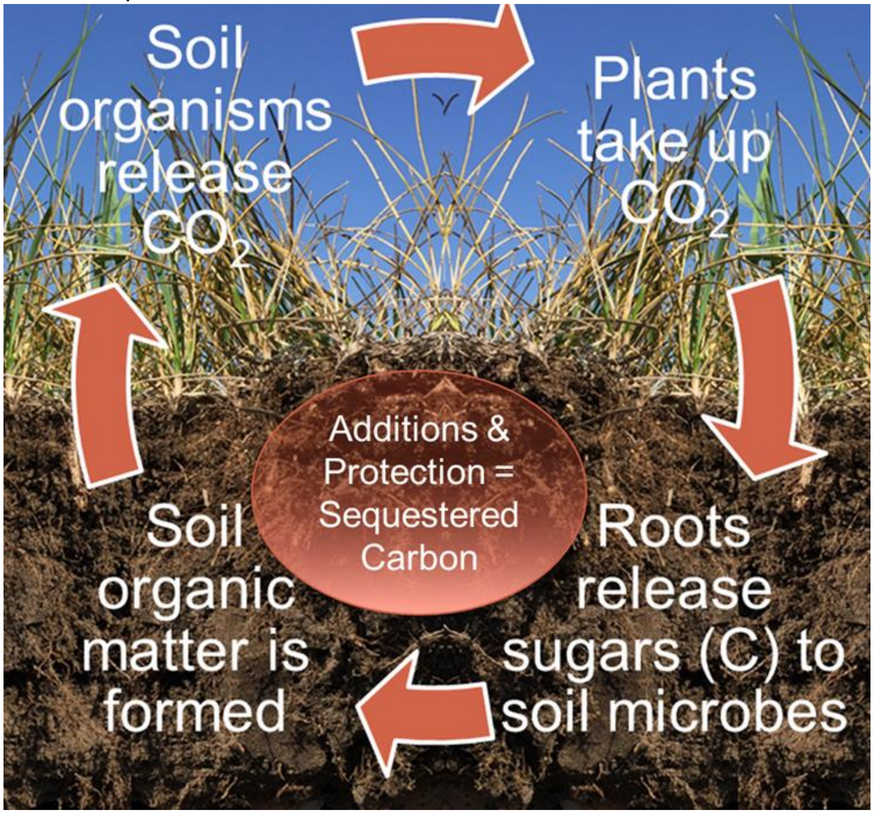

Figure 2. State-weighted average emission reduction coefficients (tonnes CO_2e ac^{-1} y^{-1}) with adoption of legume cover crop with 50% fertilizer nitrogen reduced. Weighted emission reduction coefficients generated using The CaRPE Tool, version 2.03. Values are scaled to the state level and reflect average ERCs across all counties and weighted for cropland acres. They are intended for comparative purposes only.

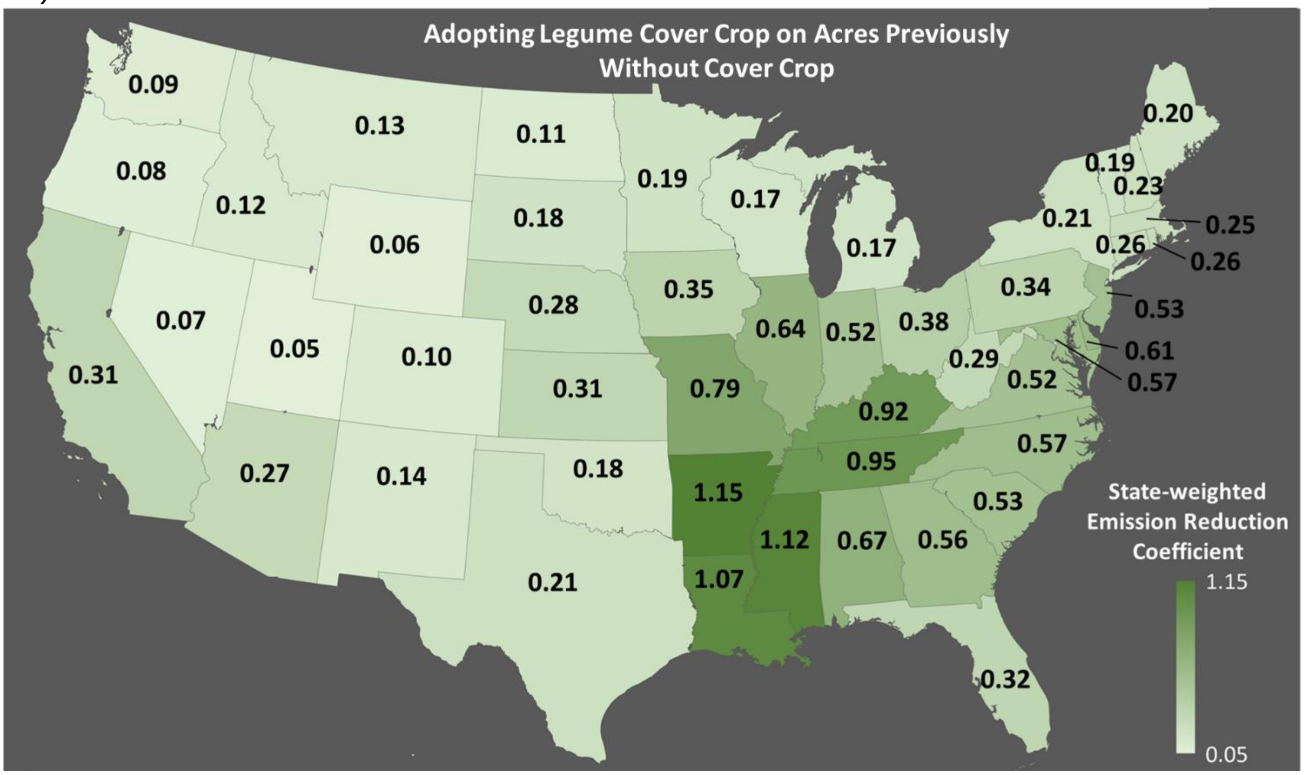

Figure 3. State-weighted average emission reduction coefficients (tonnes CO_2e ac^{-1} y^{-1}) with adoption of non-legume cover crop with 25% fertilizer nitrogen reduced. Weighted emission reduction coefficients generated using The CaRPE Tool, version 2.03. Values are scaled to the state level and reflect average ERCs across all counties and weighted for cropland acres. They are intended for comparative purposes only.

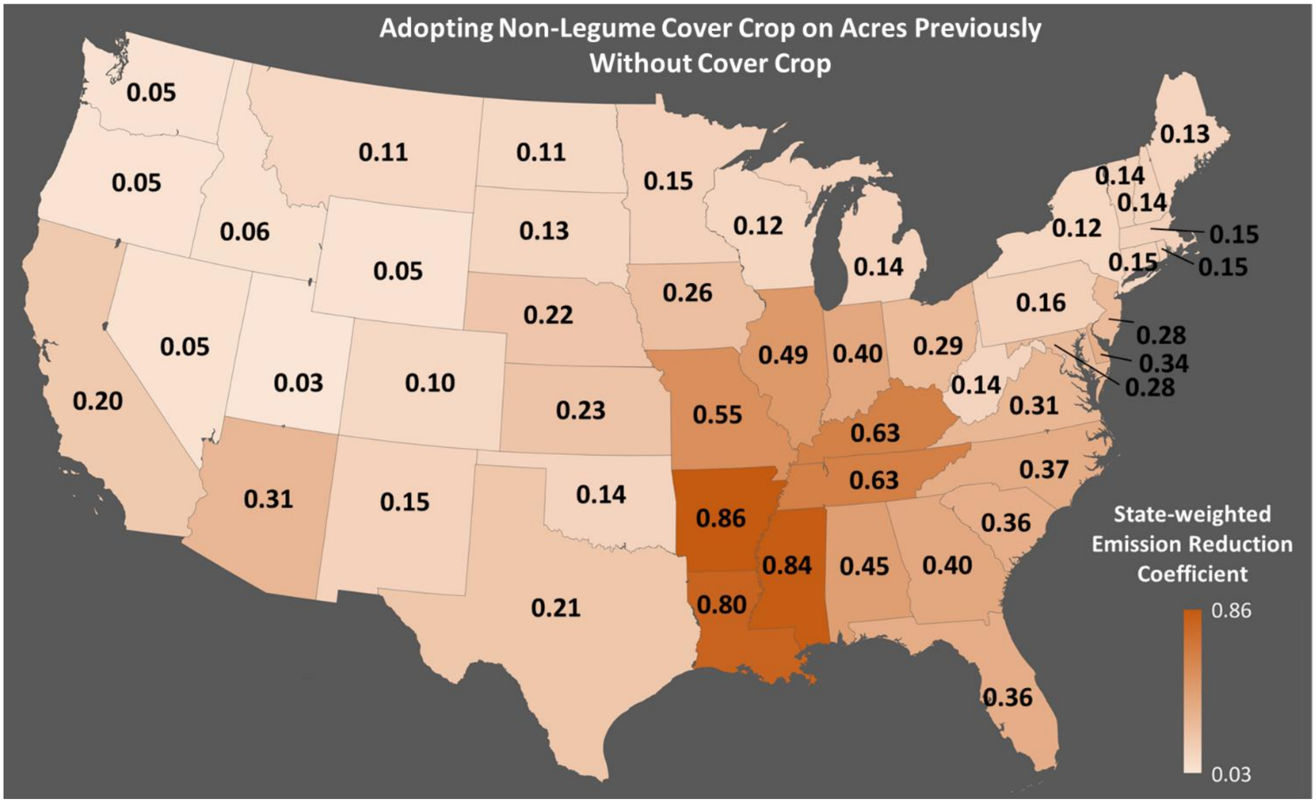

Figure 4. State-weighted average emission reduction coefficients (tonnes CO_2e ac^{-1} y^{-1}) with adoption of no-till or strip-till practices on acres formerly under intensive tillage. Weighted emission reduction coefficients generated using The CaRPE Tool, version 2.03. Values are scaled to the state level and reflect average ERCs across all counties and weighted for cropland acres. They are intended for comparative purposes only.

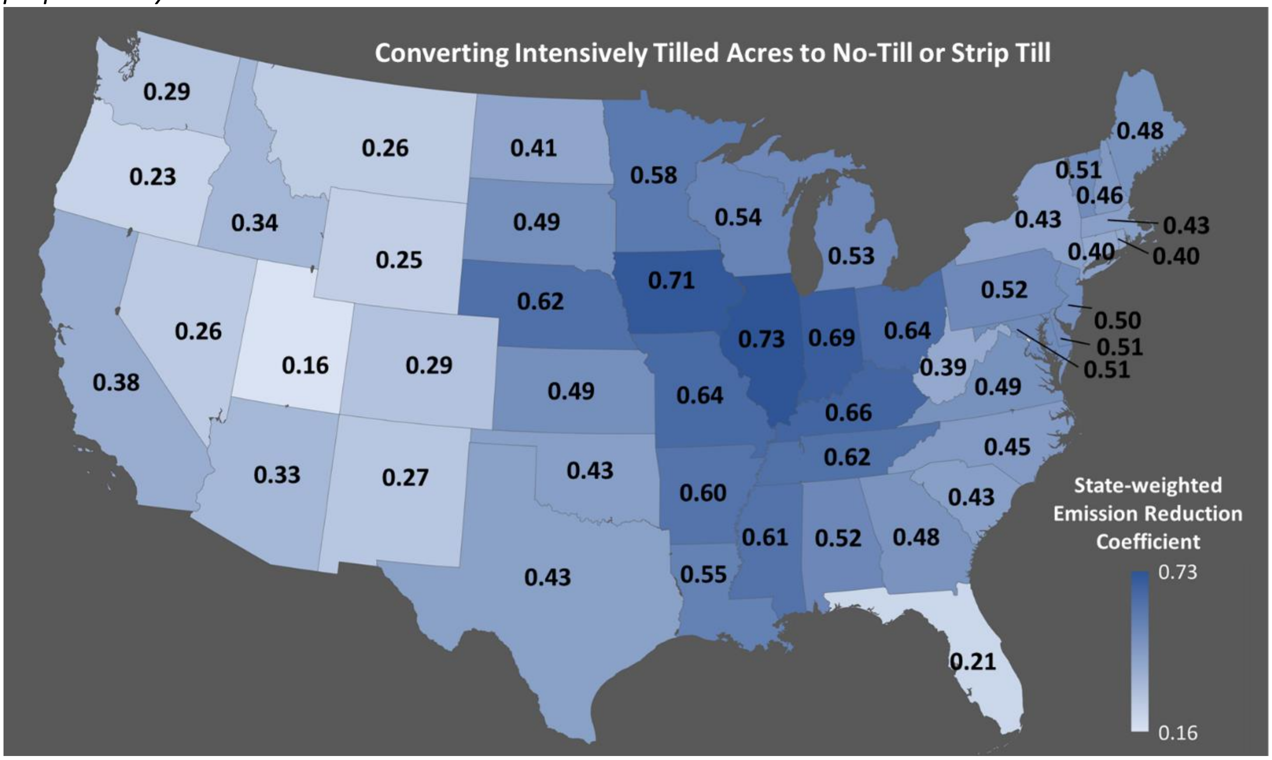

Figure 5. 2017 AgCensus total cropland acres calculated by summing county acres for each state.

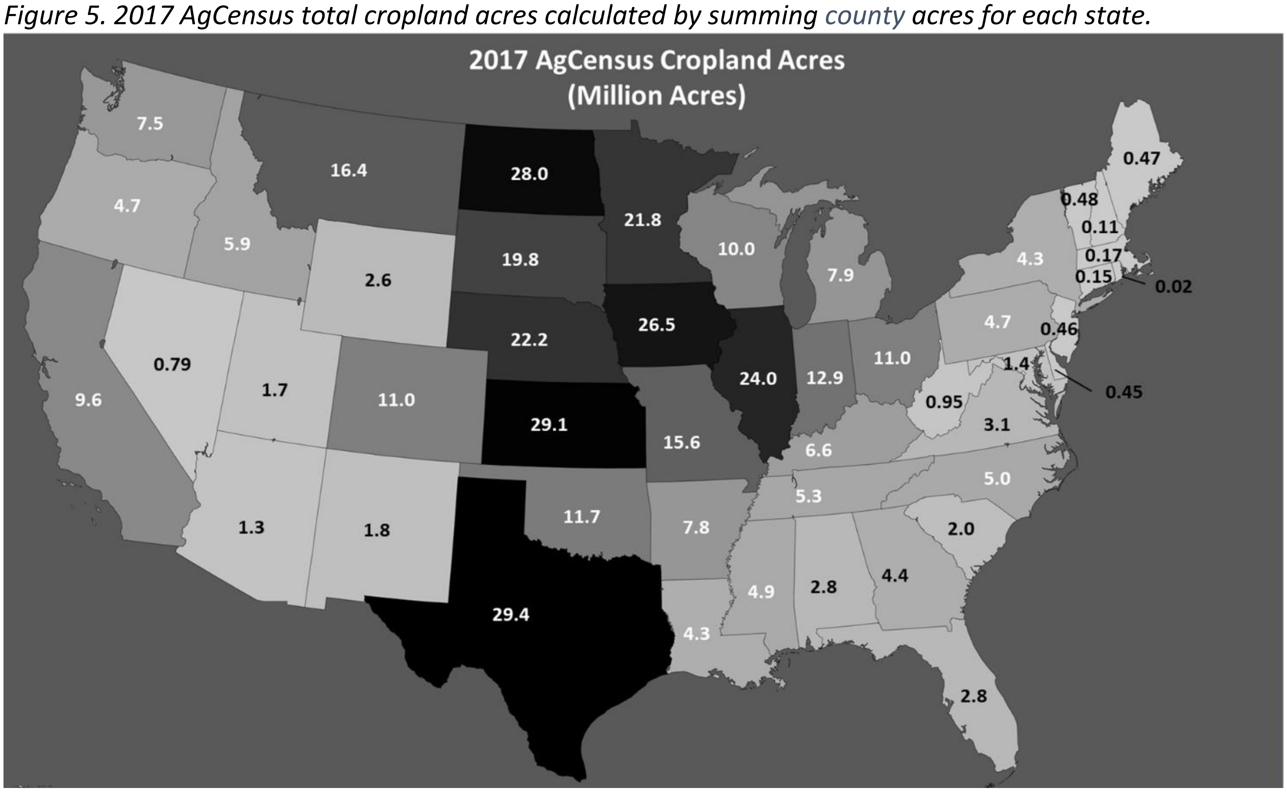

Figure 6. Total tonnes CO_2e reduced annually under the scenario where current cover crop acres and 15% of available cropland acres were planted had been planted to a legume:non-legume ratio of 25:75. Map and CO_2e reduction estimates generated using The CaRPE Tool, version 2.03.

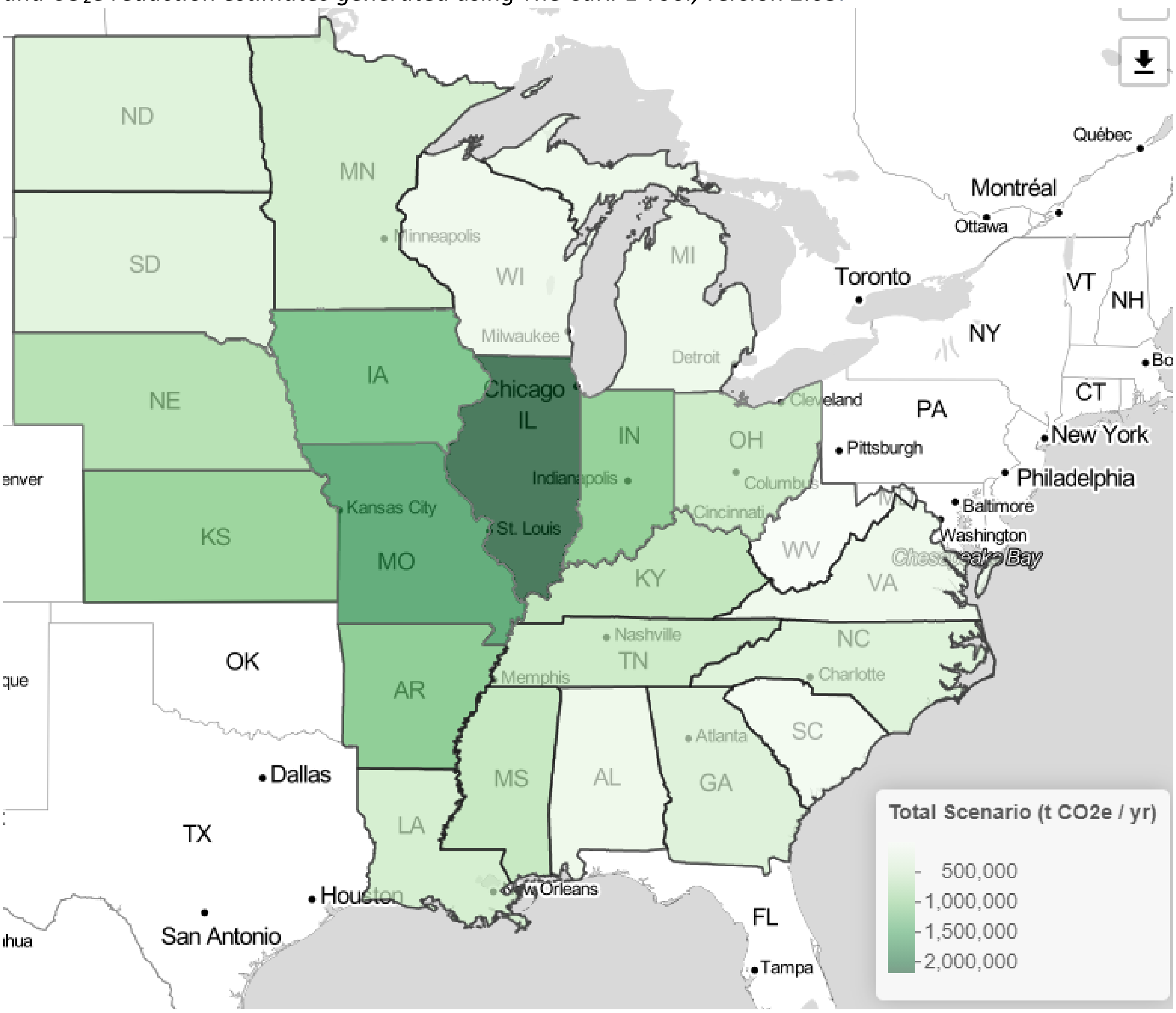

Figure 7. Total tonnes CO_2e reduced annually under the scenario where current no-till and reduced till acres had converted from intensive till and 25% of current acres in intensive till and in reduced till were converted to no-till/strip till practices. Map and CO_2e reduction estimates generated using The CaRPE Tool, version 2.03.

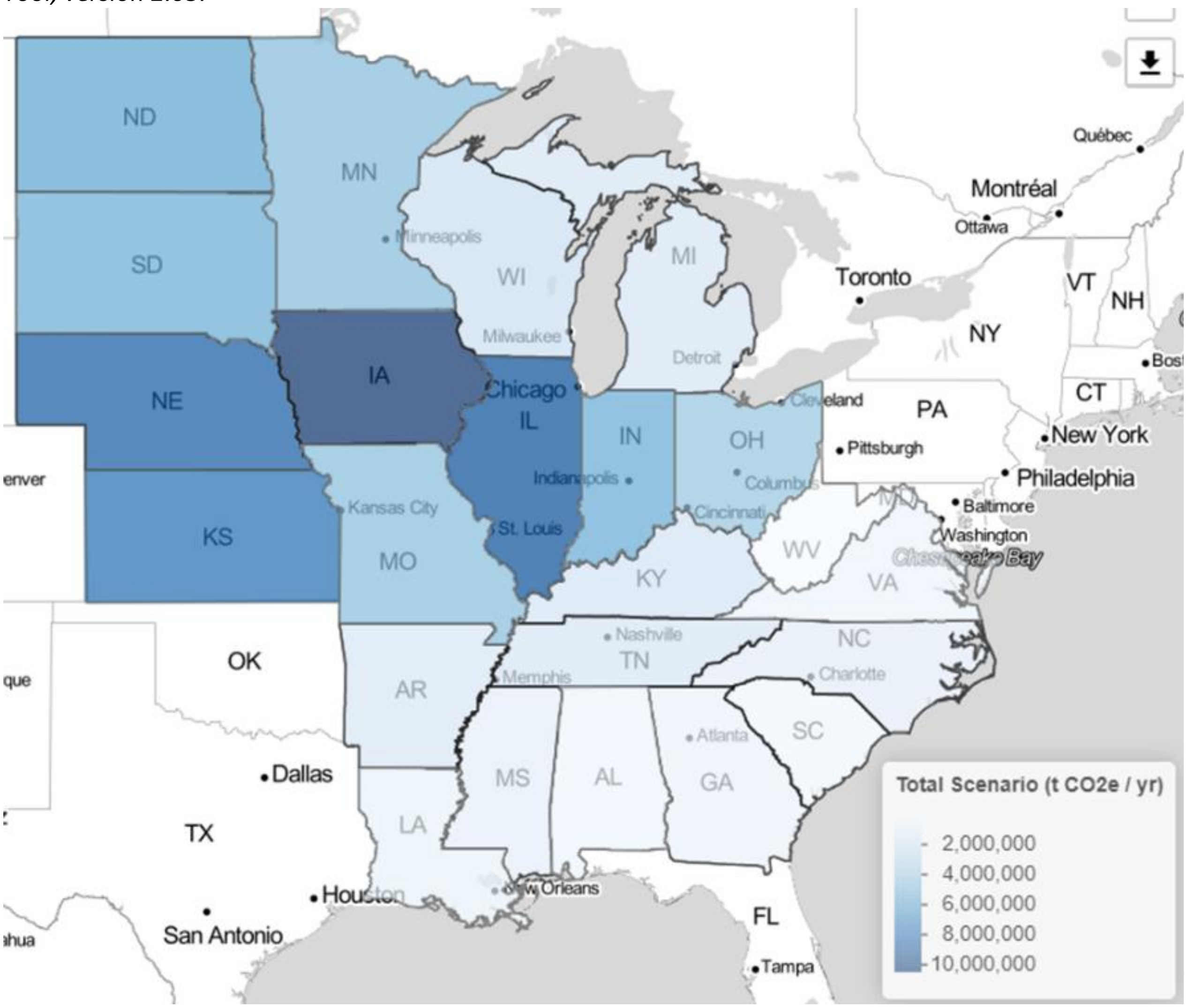

Table 1. A comparison of emission reduction coefficients (ERCs) from other US. studies/models, including climate/region of study, and soil types and depths investigated, where reported. Some studies only investigated changes in soil carbon storage while others specifically addressed cumulative GHG effects. Where appropriate, reported carbon values were converted to CO_2e for purposes of comparison.

Practice	Source	Approach	Cimate/Region, Soil Type/Depth	Avg. Practice ERC (Tonnes CO_2e ac^{-1} yr^{-1})
Cover Crops (Clover)	McNunn et al. 2020	DNDC	Corn Belt States, 50 cm	0.16
Cover Crops (Rye)	McNunn et al. 2020	DNDC	Corn Belt States, 50 cm	0.32
Cover Crops (Radish)	McNunn et al. 2020	DNDC	Corn Belt States, 50 cm	0.35
Cover Crops (75%NL, 25% L)	**This Report**	**CaRPE/COMET**	**Corn Belt and Southeast States, 30 cm**	**0.35**
Cover Crops	Sperow et al. 2020	2019 IPCC Guidelines	Warm, Temperate, Moist, 30 cm	0.45
Cover Crops	Sperow et al. 2019	2019 IPCC Guidelines	Cool, Temperate, Moist, 30 cm	0.54
Cover Crops	Eagle et al. 2012	Meta-Analysis	U.S. Croplands, Multiple Depths	0.77
No-Till	Ogle et al. 2019	Meta-Analysis	Cool, Moist - Loamy, Silty, Clayey Soils, 10 cm	0.40
No-Till	**This Report**	**CaRPE/COMET**	**Corn Belt and Southeast States, 30 cm**	**0.41**
No-Till	Ogle et al. 2019	Meta-Analysis	Warm, Moist - Loamy, Silty, Clayey Soils, 60 cm	0.49
No-Till	Ogle et al. 2019	Meta-Analysis	Cool, Moist - Sandy Soils, 40 cm	0.52
No-Till	Eagle et al. 2012	Meta-Analysis	U.S. Croplands, Multiple Depths	0.60
No-Till	McNunn et al. 2020	DNDC	Corn Belt States, 50 cm	0.60
No-Till	Ogle et al. 2019	Meta-Analysis	Warm, Moist - Sandy Soils, 35 cm	0.74
Combined Practices				
No-till, Cover Crops	Sperow et al. 2020	2019 IPCC Guidelines	Warm, Temperate, Moist, 30 cm	0.91
No-till, Cover Crops	Sperow et al. 2020	2019 IPCC Guidelines	Cool, Temperate, Moist, 30 cm	0.76
No-till, Cover Crops, Spring N	McNunn et al. 2020	DNDC	Corn Belt States, 50 cm	1.13

Abbreviations: ERC - Emission Reduction Coefficient, MMT - Million Metric Tonnes, NL - Non-legume, L - Legume, DNDC - DeNitrification-DeComposition Model, CaRPE - Carbon Reduction Potential Evaluation Tool, COMET - Carbon Management Evaluation Tool, IPCC - International Panel on Climate Change.

Table 2.<u>*Overview of cover crop scenario:*</u> *total cropland acres of selected states (including current and future cover crop adoption investigated), weighted emission reduction coefficients (ERCs) for each stage of implementation, total CO_2e reductions and notes. Acres and CO_2e reduction estimates generated using The CaRPE Tool, version 2.03. ERC values are scaled to the state level and reflect county averages weighted for cropland acres.*

	Acres (million)	ERC (Tonnes CO_2e ac^{-1} yr^{-1})	CO_2e Reduction (MMT CO_2e yr^{-1})	Notes
Total cropland in Corn Belt and Southeast	276.3	N/A	N/A	States include ND, SD, NE, KS, MN, IA, MO, IL, IN, MI, OH, WI, AL, AR, GA, KY, LA, MS, NC, SC, TN, VA, WV
Acres available for cover crops	232.3	N/A	N/A	Total cropland minus current cover crop acres minus acres in hay
Current cover crops	11.0	0.39	4.3	75% non-legume, 25% legume
New cover crop acres	34.8	0.34	11.9	15% of available cover crop acres; 75% non-legume, 25% legume
Total scenario	45.9	0.35	16.1	75% non-legume, 25% legume

Note: Numbers may not add up exactly due to rounding.

Table 3. <u>Overview of tillage scenario:</u> total cropland acres of selected states (including current and future no-till adoption investigated), weighted emission reduction coefficients (ERCs) for each stage of implementation, total CO_2e reductions and notes for the tillage scenario. Acres and CO_2e reduction estimates generated using The CaRPE Tool, version 2.03. ERC values are scaled to the state level and reflect county averages weighted for cropland acres.

	Acres (million)	ERC (Tonnes CO_2e ac^{-1} yr^{-1})	CO_2e Reduction (MMT CO_2e yr^{-1})	Notes
Total cropland in Corn Belt and Southeast	276.3			States include ND, SD, NE, KS, MN, IA, MO, IL, IN, MI, OH, WI, AL, AR, GA, KY, LA, MS, NC, SC, TN, VA, WV
Acres currently in no-till	82.1	0.59	48.4	Assumes acres were converted from intensive till to no-till
Acres currently in reduced till	79.4	0.12	14.9	Assumes acres were converted from intensive till to reduced till
Acres currently in intensive till	56.2	N/A	N/A	
New no-till acres	33.9	0.52	17.7	Assumes 25% of current reduced till acres and 25% of current intensive till acres convert to no-till
Total scenario	195.4	0.41	81.0	Current reductions from acres already in no-till and reduced till + new acres converting to no-till

Note: Numbers may not add up exactly due to rounding.

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