U.S. DEPARTMENT OF AGRICULTURE

DOCUMENTATION OF LITERATURE, DATA, AND MODELING ANALYSIS TO SUPPORT THE TREATMENT OF CSA PRACTICES THAT REDUCE AGRICULTURAL SOIL CARBON DIOXIDE EMISSIONS AND INCREASE CARBON STORAGE

Office of Energy and Environmental Policy
Office of the Chief Economist

January 2025

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SUMMARY

This white paper provides the rationale and evidence that changes in soil organic carbon (SOC) stocks due to the implementation of climate-smart agriculture (CSA) practices help address the buildup of greenhouse gases in the atmosphere and that the reductions in net carbon dioxide emissions are persistent over time. Two types of CSA practices can provide significant carbon storage benefits: shifts from intensive tillage to no-till and reduced-till and the deployment of cover crops.

This white paper is divided into the following sections: (1) background on soil organic carbon (SOC) accumulation, storage, and durability, (2) national trends that indicate carbon stocks in cultivated mineral soil are increasing, (3) evidence of how CSA practices reduce carbon emissions and increase sequestration, (4) current rates and recent national trends in CSA practice adoption, (5) evidence of persistence of CSA practice adoption, (6) a description of the evidence indicating the durability of carbon flux changes through the use of CSA practices.

1. BACKGROUND ON SOIL ORGANIC CARBON ACCUMULATION, STORAGE, AND DURABILITY

Carbon in cropland ecosystems is contained in above-ground and below-ground biomass, dead organic matter, and soils. Carbon stored in soil, primarily as organic molecules, is commonly referred to as soil organic matter (SOM). Soil organic carbon (SOC) is the carbon portion of SOM and is measured to evaluate carbon sequestration and accumulation in soils. Carbon stock changes can be positive (resulting in the sequestration of carbon) or negative (resulting in the emissions of carbon dioxide). In addition to carbon, SOM also contains several other elements including nitrogen, phosphorus, sulfur, potassium and calcium. Taken as a whole, SOM serves as the primary mechanism for the long-term storage of soil carbon, and deep soils can store carbon for centuries, or even millennia (Campbell et al., 1967; Scharpenseel and Becker-Heidmann, 1989; Krull and Skjemstad, 2003). However, not all SOM carbon is as durable as the deep soil pool. Some of the carbon stored in SOM can be quickly metabolized and decomposed by microbes on the time scale of days to decades.

Most agro-ecosystem models used to quantify carbon accumulation in soils, including DayCent and SALUS, recognize this difference in SOM recalcitrance, and separate SOM into distinct pools (e.g., active, slow, and passive), each with its own mean residence time. The DayCent model is used to quantify greenhouse gas fluxes for the agricultural sector for the U.S. Inventory of Greenhouse Gas Emissions and Sinks.

2. NATIONAL CULTIVATED CROPLAND SOIL ORGANIC CARBON TRENDS

The Inventory of U.S. Greenhouse Gas Emissions and Sinks (the Inventory) provides a time series of data showing changes in carbon in cropland ecosystems (specifically defined as the cropland remaining cropland category).

The carbon content and rate of change of carbon stored in mineral soils reported in the Inventory is dependent on climate, temperature, and soil type, as well as agricultural practices such as tillage, clearing, planting, grazing, drainage, fertilization, crop residue management, the application of biosolids, and flooding. (Paustian et al., 1997a; Lal, 1998; Conant et al., 2001; Ogle et al., 2005; Griscom et al., 2017; Ogle et al., 2019). In 2022, the Inventory showed that mineral soils in the U.S. are a substantial carbon sink, storing an estimated 62.0 MMT CO2 equivalent (CO2e) – a more than 58 percent increase since 1990. This level of carbon storage offsets roughly 10 percent of all agricultural greenhouse gas emissions (EPA, 2024).

The primary drivers behind increases to SOC stocks over time in the Inventory cropland remaining cropland category include reduced and no-till practices, expansion of cover crops, annual crop production with hay or pasture in rotations, manure amendments, and land set-aside from production in USDA's Conservation Reserve Program (Ogle et al., 2023).[1] Between 1990 and 2022, changes in the mineral soil carbon stock in this category vary between 38.2 and 69.6 MMT CO2e, with a mean value of 55.9 MMTCO2e (EPA, 2024).

3. CSA PRACTICES THAT REDUCE SOIL CARBON EMISSIONS AND INCREASE CARBON SEQUESTRATION

As indicated by the Inventory data, practices used on agricultural lands to raise crops greatly influence SOC. Historically, tillage has been an integral component of land cultivation. Tillage is performed for several reasons, including loosening and aerating topsoil, mixing residue into the soil, mechanically destroying weeds, and drying soils before seeding. Tillage can be categorized into intensive tillage (also known as conventional tillage), reduced till, and no-till, depending on the level of soil disturbance resulting from tillage implements used and number of passes. Intensive tillage results in a full inversion or mixing of the soil with implements such as a moldboard plow or deep disking, which result in low surface coverage of residue (Hanson et al., 2024). Intensive tillage has a several drawbacks. As heavy farm machinery makes passes across a field during a tillage operation, soil compaction occurs. Over time this compaction can create a hard, impermeable pan that reduces the rate of water infiltration and drainage, restricts root growth, reduces oxygen in the root zone, and results in higher N2O emissions through increased denitrification. Additional subsoil tillage can help alleviate compaction in the short-term, however the additional equipment passes often cause soil to re-compact. Tillage passes made during intensive tillage and subsoil tillage operations increase costs to farmers in the form of increased energy costs. In addition to issues related to compaction, intensive tillage also leaves soil susceptible to erosion from wind and water, and breaks soil aggregates, exposing soil carbon to microbes and creating conditions favorable to increased decomposition of carbon stored in SOM (Hakansson and Reeder, 1994; Lal, 2004; Reeder and Westermann, 2006).

No-till (NT) is a climate-smart practice that limits soil disturbance to manage the amount, orientation and distribution of crop and plant residue on the soil surface year-round. NT results in a soil tillage intensity rating (STIR)[2] value that is no greater than 20. Residue retention on the soil

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[1] Winter cover crops had a negligible influence on SOC due the small area in cover crops in the United States over the study period.

[2] STIR is a numerical value that measures the severity and type of soil disturbance caused by tillage operations. STIR values range from 0 to 200, with higher values indicating more soil disturbance. The STIR

surface adds organic matter, which decomposes over time and increases soil fertility, but also contributes to the buildup of soil organic matter, a key component of soil carbon storage (Lal, 2004; Six et al., 2002). The decomposition of residues is slower under NT compared to intensive tillage, because the presence of residues on the surface slows the temperature of the soil surface, which allows more carbon to be retained in the soil over time. NT significantly reduces the oxidation of organic matter, thereby decreasing CO_2 emissions (West and Post, 2002). NT promotes the formation of stable soil aggregates, which physically protect organic carbon from microbial decomposition. These aggregates prevent organic matter from being easily broken down and released as CO_2 into the atmosphere (Six et al., 2002). Aggregation also improves soil porosity and water infiltration, creating a more favorable environment for carbon accrual. Most carbon accumulation in no-tillage systems occurs in the topsoil (0–30 cm). The effectiveness of NT in reducing carbon losses and sequestering soil carbon depends on several factors, including: (1) climate: warmer, wetter climates tend to enhance residue decomposition, reducing the net carbon gain, while cooler climates may promote greater carbon retention; (2) soil type: clay-rich soils often exhibit higher carbon stabilization due to their greater aggregation potential and protection factor, while sandy soils may show limited carbon sequestration; and (3) cropping system: diverse crop rotations and high-residue crops (e.g., corn, wheat) are more effective at increasing soil carbon compared to low-residue crops (e.g., soybeans) (Powlson et al., 2014). Long-term implementation, combined with complementary practices like cover cropping, is essential to maximize its benefits.

Reduced tillage (RT) involves minimal soil disturbance compared to conventional tillage but involves occasional non-inversion layer tillage. RT results in a STIR value that is no greater than 80. While less effective than NT, RT still limits organic matter oxidation and promotes some level of carbon retention (Paustian et al., 2016). RT integrates crop residues into the soil, enhancing carbon inputs. RT reduces erosion compared to intensive tillage preventing carbon loss through sediment transport. Cover crops are grasses, legumes, and forbs planted for seasonal vegetative cover, and not intended for harvest, between harvested production crops in rotation (NRCS, 2024). Cover crops protect and add organic matter to the soil. Cover crops contribute organic matter through their biomass (roots and residues), which decomposes and increases soil carbon (Bolinder et. al, 2020; Don and Poeplau, 2015; Kaye and Quemada, 2017). The additional organic matter from cover crops stimulates soil microbial populations, which play a role in enhancing carbon stocks. Cover crop roots enhance soil aggregation, physically protecting organic carbon. Cover crops prevent carbon loss through erosion and runoff by stabilizing soil surface (Qui et al., 2024). The effectiveness of cover crops depends on time of planting, termination, species selection, biomass production, and how residues are managed post-termination (NRCS, 2024).

4. CURRENT RATES AND RECENT NATIONAL TRENDS IN CSA PRACTICE ADOPTION

Given the greenhouse gas benefits associated with practices such as no-till, reduced till, and cover crops, monitoring adoption and retention rates of these practices can serve as an important indicator of the size of the carbon sink of U.S. agriculture and indicate how the sink is changing over time.

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rating applies to the entire tillage system used in producing a crop. The components of the rating include tillage type, recommended equipment operating speed, recommended tillage depth, and surface area disturbed.

Data from the 2022 Census of Agriculture shows American farmers added more than 756,000 acres to no-till production since the 2017 Census. In 2022, more than 105.2 million acres were in no-till production, around 35% of all harvested cropland acres, compared to more than 104.45 million acres in 2017. This change represents a 1% increase in no-till acres relative to 2017. Reduced till acres decreased by 692,675 acres between 2017 and 2022, but the number of farms using conservation or reduced till increased by 11,152. We can assume that at least part of this decrease in acreage may be attributable to farmers transitioning to no-till practices. Cover-cropped acres went up about 17% over the same time-period.

USDA's Agricultural Resource Management Survey (ARMS) provides crop-specific data on the rates of adoption of conservation practices used by U.S. farmers. ARMS is a survey that relies on a representative sample of agricultural producers in the main states producing specific commodities to evaluate national trends in agricultural production. ARMS surveys are crop-specific and cover the three main crops used for biofuel feedstocks: field corn, sorghum, and soybeans. These crops are surveyed periodically with the most recent surveys conducted in 2021 for corn, 2019 for sorghum, and 2023 for soybeans.

ARMS data indicate that in the most recent survey years, 35.6% of field corn acres in 2021, 58.8% of sorghum producer acres in 2019, and 44.8% of soybean acres in 2023 were in no-till. An additional 39.9% of field corn acres, 16.7% of sorghum acres, and 35.9% of soybean acres were in reduced tillage. Combined these data indicate that the vast majority of acres in field corn, sorghum, and soybeans are in either reduced or no-till.

Table 4.1. Rates of reduced till, No-till, and cover cropping as reported in crop specific ARMS surveys for field corn (2021), sorghum (2019), and soybeans (2023).[3]

	Field corn	**Sorghum**	**Soybeans**
	2021	**2019**	**2023**
Percent of planted acres by tillage type:			
Intensive Till	24.5	24.4	19.3
Reduced till	39.9	16.7	35.9
No-till	35.6	58.8	44.8
Percent acres with cover crop	8.1	0.7	11.3

5. EVIDENCE OF PERSISTENCE OF CSA PRACTICE ADOPTION AMONG US FARMERS

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[3] Data notes: We report tillage statistics from two parts of the ARMS Phase 2 surveys for corn (2021), sorghum (2019), and soybeans (2023). First, producer fields reporting any tillage operations are classified as either intensive till or reduced till for the survey year, based on their estimated soil tillage intensity rating (STIR). See Claassen et al. 2018 for more detail (https://www.ers.usda.gov/publications/pub-details/?pubid=90200). Fields reporting no tillage operations are classified as no-till using the STIR classification. We also provide the current year percentage in cover crops.

The persistence or longevity of CSA practice adoption has important implications for the environmental and climate benefits that these practices generate. To maximize the greenhouse gas benefits of soil carbon CSA practices, the practices should be implemented consistently over time. While implementation in a single year will reduce carbon emissions and store additional carbon, implementing the practices consistently over time helps to ensure that additional stored carbon is maintained. This is especially the case for tillage, where a reversion to intensive tillage can potentially lead to carbon losses over time. When considering the long-term carbon benefits of reduced and no-till practices, one consideration is the likelihood that, once initiated, farmers will continue with the CSA practice in the future.

A farmer's decision to maintain or discontinue a CSA practice is complex, driven by economic and financial conditions, agronomic factors, and policy. The costs of CSA practice maintenance, impact on yields, and operation profitability are critical considerations for farmers. Changes in economic conditions, such as changes in market prices for commodity crops can also factor into a farmer's decision to maintain or discontinue CSA practices. Agronomic and farm-level environmental challenges such as changes in pest pressures, weather, and climate factors can also influence whether a farmer can feasibly continue using a practice. The policy and regulatory context can also influence farmer decision-making around practice maintenance. The availability of technical assistance or financial incentives for practice adoption can help spur adoption and potentially ensure longer-term use. Farmers' personal motivations for adopting CSA practices, such as interest in generating public goods (i.e., improved water quality, enhanced biodiversity, or climate benefits) also may affect persistence or longevity of practices.

While additional studies are needed to understand longer-term persistence or longevity of CSA practice adoption, recent nationally representative data indicates that reduced tillage and no-till in particular have relatively high levels of short-term persistence. USDA data from the most recent Agricultural Resource Manage Survey (ARMS)[4] of field corn (2021), sorghum (2019), and soybean (2023) producers indicates that over five years of reported cropping history, 89% of field corn acres

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[4] Data notes: We report tillage statistics from two parts of the ARMS Phase 2 surveys for corn (2021), sorghum (2019), and soybeans (2023). First, producer fields reporting any tillage operations are classified as either intensive till or reduced till for the survey year, based on their estimated soil tillage intensity rating (STIR). See Claassen et al. 2018 for more detail (https://www.ers.usda.gov/publications/pub-details/?pubid=90200). Fields reporting no tillage operations are classified as no-till using the STIR classification. Table 5.1 provides results only for producers whose fields were classified as using no-till for the current survey year. For this subset of producers, the percentage of producer fields with 1, 2, 3, 4, or 5 years of no-till or strip till (strip till is a practice that limits soil disturbance to the crop planting or seeding area. In USDA conservation programs, strip tillage is permitted in no-till systems, provided that the overall crop interval STIR value is no greater than 20 (NRCS, 2016). in their cropping history is calculated based on a separate survey questions focused on cropping history. Table 5.2 provides results only for producers whose fields were classified as using reduced till for the current survey year. For this subset of producers, the percentage of producer fields with 1, 2, 3, 4, or 5 years of no-till or strip till in their cropping history is calculated based on a separate survey question focused on cropping history. ARMS questionnaires can be found at: https://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/questionnaires-and-manuals/.

classified as no-till (2021) were in no-till or strip till[5] in 4 or 5 of the previous 5 years of cropping history. Similarly, 79% of soybean acres in no-till in the current survey year (2023) were in no till no-till or strip till in 4 or 5 of the previous 5 years. Conversely, sorghum acres using no-till in the current survey year had lower levels of more continuous adoption of no-till or strip tillage over the 5-year crop history period. The ARMS cropping history questions do not separate out no-till and strip till use, although strip till is a practice that limits soil disturbance to the crop planting or seeding area. In USDA conservation programs, strip tillage is permitted in no-till systems, provided that the overall crop interval STIR value is no greater than 20 (NRCS, 2016).

Table 5.1. Percent of acreage in no-till or strip till[6] over five years of cropping history if no-till was reported in the current survey year

	Corn %	Sorghum %	Soybeans %
	2021	**2019**	**2023**
Percent acres in no-till in current survey year	36	59	45
Of acres in no-till in current survey year, percent acres by years in no/strip till:			
1 of 5 years in no/strip till	3	18	4
2 of 5 years in no/strip till	4	35	5
3 of 5 years in no/strip till	4	19	12
4 of 5 years in no/strip till	10	16	7
5 of 5 years in no/strip till	79	12	72
Total	100	100	100

For acreage reported in reduced till in the current survey years, 5-year persistence rates of no-till/strip till were lower relative to the acres reported in no-till in the current survey year. Table 5.2 summarizes these results. 59% of corn and 62% of soybean acres reported in reduced till in the current survey year were in no-till or strip till in 4 to 5 out of 5 years of their cropping history.

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[5] Strip till is a practice that limits soil disturbance to the crop planting or seeding area. In USDA conservation programs, strip tillage is permitted in no-till systems, provided that the overall crop interval STIR value is no greater than 20 (NRCS, 2016).

[6] Strip till is a practice that limits soil disturbance to the crop planting or seeding area. In USDA conservation programs, strip tillage is permitted in no-till systems, provided that the overall crop interval STIR value is no greater than 20 (NRCS, 2016).

Table 5.2. Percent of acreage in no-till or strip till[7] over five years of cropping history if reduced till was reported in the current survey year

	Corn	Sorghum	Soybeans
	2021	2019	2023
Percent acres in no-till in current survey year	40	17	36
Of acres in no-till in current survey year, percent acres by years in no/strip till:			
1 of 5 years in no/strip till	3	15	14
2 of 5 years in no/strip till	26	36	12
3 of 5 years in no/strip till	12	17	12
4 of 5 years in no/strip till	11	9	11
5 of 5 years in no/strip till	48	22	51
Total	100	100	100

Empirical studies evaluating rates of CSA practice persistence rates have mostly focused on how expiration of policies that provide incentive or technical assistance for practice adoption affect persistence rates. These studies have been limited to evaluating short-term persistence rates, but results indicate high levels of persistence after incentives or programs expire. For example, a 2010 study of the Little Bear Watershed Project in Washington State found that 66% of conservation management practices (including no-till and reduced till) that had been partially or fully implemented persisted a year after the program officially ended (Jackson-Smith et. al, 2010). A study using satellite data and USDA Agricultural Risk Management Survey (ARMS) data to evaluate persistence of no-till from 2010-2013 for several commodity crops found that adoption had relatively high persistence rates (up to 90% for field corn or soybeans) after USDA Environmental Quality Incentives (EQIP) contracts expired (Wallander et. al, 2017). A 2024 study focused on the Mississippi Delta region (including Arkansas, Mississippi, and Louisiana) from 2005 to 2022 found that cover crops had a 70% probability of persistence after EQIP and CSP contract expiration; 79% for conservation crop rotations; 69% for conservation tillage; and 91% for nutrient and irrigation management (Pathak et. al, 2024). Wade and Claassen (2017) found that farmers who adopt no-till practices tend to maintain them over time, particularly when the practices align with local agricultural conditions and economic incentives.

More research is needed, especially to evaluate long-term practice persistence rates. The primary challenge in evaluating persistence or longevity of CSA practice adoption is lack of appropriate data. In particular, collecting data that allows for tracking farm-level CSA practice adoption over a longer time horizon is challenging. For example, long term studies are costly and present significant logistical challenges. It may also be challenging to maintain communication with the same

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[7] Strip till is a practice that limits soil disturbance to the crop planting or seeding area. In USDA conservation programs, strip tillage is permitted in no-till systems, provided that the overall crop interval STIR value is no greater than 20 (NRCS, 2016).

producers over a long time period. While these studies only looked at short-term persistence rates, they demonstrate that producers have a high propensity to continue adoption even without the types of supports offered by USDA conservation programs or other policies that help offset costs or other barriers to practice adoption.

In addition to estimating practice persistence rates, these studies provide insight into likely reasons why farmers tend to continue implementing conservation (including no and reduced) tillage and cover crops once these practices are adopted and after program or policy supports cease. The effectiveness of one-time payments or incentive programs indicates that up-front costs may be a significant barrier to conservation tillage adoption, and that once these costs are addressed, adoption is likely to continue (Wallander et. al, 2017). These studies also indicate that programs may be effective at addressing initial learning and human capital costs that pose similar short-term barriers to adoption, that then allow for persistence (Wallander et. al, 2017).

Separately, persistence in conservation tillage (including reduced and no-till) and cover crop adoption may be a direct result of the short and long-term benefits that farmers realize from these practices that outweigh costs that were previously offset by programs or policies. For instance, no-till reduces several operational and labor costs by cutting out the need to spend time, fuel, and effort on tillage (Claassen et. al, 2018). In the long-term, conservation tillage can lead to improved water quality, reduced erosion and nutrient runoff, and improved wildlife habitat, benefits which can both accrue directly to the farmer and to the environment (Pathak et. al, 2024). Cover crops are associated with many similar long-term benefits and can enhance the overall resiliency of agricultural land to extreme weather (Pathak et. al, 2024). In addition, cover crop usage may lead to a reduced need for herbicide and pesticide usage, depending on the cover crop used (Pathak et. al, 2024). The various benefits associated with these climate-smart practices can provide lasting, non-monetary incentives for continued adoption.

6. DURABILITY OF CARBON FLUX CHANGES THROUGH CSA PRACTICES

As discussed above, farmers are likely to persist in the implementation of conservation practices after their initial adoption. However, it is important to acknowledge cases in which farmers either revert from conservation practices to conventional practices, or cases in which farmers implement conventional practices intermittently with conservation practices. A key question in these cases is the extent to which occasional conventional activities adversely affect the soil carbon accumulation resulting from previous years of conservation practices – in other words, how “durable” are changes in soil carbon through changes in agricultural practices? Among these cases, the use of intermittent tillage within the broader practice of no-till is of particular interest, as producers may alternate no-till with more disruptive tillage practices (Claassen et. al, 2018).

Many studies have assessed this question by analyzing the impacts of intermittent tillage, both intensive and reduced, on soil carbon accumulation in fields that were primarily or previously no-till. A literature review of these studies reveals that even when there is occasional reversion to non-CSA tillage practices, the benefits from the years of no-till implementation are maintained over time.

Literature Review

Several recent studies have concluded that agricultural management changes are unlikely to result in loss of all newly stored soil carbon. These studies focus on the conversion of no-till fields to intermittent tillage. These studies found that infrequent tillage events do not result in significant C loss relative to no-till (Conant et al., 2007; Dimassi et al., 2013; Ogle, 2019; Blanco-Canqui and Wortmann, 2020).

Recent synthesis studies and meta-analyses provide robust evidence supporting the durability of soil carbon storage under climate-smart agricultural practices, even with occasional disruptions to management practices. A comprehensive review by Blanco-Canqui and Wortmann (2020) found that occasional tillage in no-till systems generally has limited adverse impacts on long-term soil carbon accumulation. Their analysis revealed that when occasional tillage appears to reduce soil carbon near the surface, it typically transfers that carbon to lower depths rather than losing it entirely. Furthermore, they identified key factors influencing successful implementation of occasional tillage, including method, depth, frequency, and timing, suggesting that when implemented thoughtfully - for example, once every 5-10 years - it can address agronomic challenges while maintaining ecosystem services.

These conclusions are reinforced by earlier meta-analyses addressing the quantitative impacts of periodic tillage on soil carbon stocks. Conant et al. (2007) found that periodic tillage every 4-6 years reduces soil carbon by only approximately 6% compared to continuous no-till, while retaining the majority of no-till-induced carbon gains. Ogle et al. (2019) demonstrated that carbon storage effectiveness varies by climate and soil characteristics, with the combination of no-till, residue retention, and cover crops enhancing resilience even when occasional tillage is necessary. These integrated approaches illustrate that carbon storage durability depends not just on tillage practices alone, but on the broader suite of agricultural management decisions.

Field studies across different agricultural regions and conditions provide additional evidence for carbon storage durability. Dimassi et al. (2013) conducted a 41-year experiment showing that while reduced tillage causes initial carbon redistribution in soil profiles, overall carbon stocks remain stable over long periods. This aligns with recent research by Thapa et al. (2023), which found no significant differences in soil organic carbon concentrations between no-till and occasional tillage at most sampling points. Similarly, Paye et al. (2024) found that occasional tillage resulted in higher macro-aggregate proportions (51–54%) compared to intensive tillage (CT) (44%), indicating improved soil structural stability under reduced tillage. Results suggest that frequent intensive tillage reduces SOC and nitrogen storage. However, a single intermittent tillage event after several years of NT does not significantly impact SOC, nitrogen dynamics, or soil structural stability in semi-arid drylands.

Dang et al. (2015) examined the impacts of occasional intermittent tillage within no-till farming systems in Australia's northern grain-growing regions. They found that a single tillage event can temporarily decrease soil organic carbon levels, likely due to disturbance of organic matter and increased microbial activity. However, the long-term effects on SOC stocks were variable and often minimal, suggesting that soil systems may possess inherent resilience to occasional disturbance. This indicates that no-till farming systems with judicious application of intermittent tillage may be able to maintain soil carbon levels comparable to continuous no-till, provided the broader management approach emphasizes building soil organic matter over time.

The interpretation of soil carbon storage data requires careful consideration of measurement depth and statistical power. Kravchenko and Robertson (2011) highlight that the absence of statistically significant differences in whole-profile carbon stocks should not be interpreted as evidence that management practices have no effect on carbon storage. Their analysis illustrates that the high variability in soil carbon measurements at depth, combined with typically limited sampling, makes it extremely difficult to detect even substantial changes in deep soil carbon stocks. This is particularly relevant for no-till systems, where root growth patterns can distribute carbon more deeply in the soil profile compared to intensive tillage. The authors argue that carbon stock changes should be analyzed by soil layer rather than whole profiles, as significant changes in surface layers may be obscured by variability at depth.

The conclusion that can be drawn from this literature is that while continuous no-till systems may maximize carbon storage potential, modest disruptions through intermittent tillage do not significantly compromise long-term carbon gains. When combined with complementary practices such as cover crops and crop rotation, these systems show resilience in maintaining soil carbon stocks even with periodic management adjustments.

Modeling the Effect of Intermittent Tillage on the Durability of Stored Carbon using the SALUS Model

The SALUS (System Approach to Land Use Sustainability) process-based crop model simulates at daily time step the interactions between soil, climate, genetics and management and their effects on crop growth and yield and on environmental outcomes (e.g., nitrate leaching, greenhouse gas emissions, soil carbon sequestration) (Basso et al., 2006, Basso and Ritchie, 2015).

SALUS was used to evaluate the effects of intermittent tillage on soil carbon emissions and sequestration. For this analysis, MSU developed 20 model farms in four states (IA, IL, OH, and SD). The analysis utilized a baseline of intensive tillage for an alternating corn-soybean rotation over a 20-year period. These simulations were repeated for several alternative scenarios, including continuous no-till, continuous no-till with a winter cover crop, reduced tillage, an intermittent tillage scenario that alternated between no-till corn and intensively tilled soybeans, and a partial tillage scenario that simulated three years of continuous no-till followed by 27 years of intensive tillage. Even with the highest incidence of intensive tillage (i.e., three years of no-till followed by 27 years of intensive tillage), the modeled results showed reductions in carbon emissions and increases in sequestration compared to continuous intensive tillage. The process and results of the analysis can be found below.

Tillage assumptions used in SALUS Intermittent Tillage Analysis

Intensive tillage results in a high level of soil disturbance and typically involves multiple tillage passes. The intensive tillage scenario was defined with two tillage passes, a chisel plow to 20 cm depth in the spring 7 days prior to planting and a field cultivator to 10cm depth 1 day prior to planting.

Reduced tillage, also known as minimum tillage, is less invasive than intensive tillage, typically involving only one tillage event and a smaller area of disturbance. The reduced tillage scenario was defined as a single tillage event using a tandem disk to 10cm depth in the spring 1 day prior to planting.

No-till was defined as where the soil remained undisturbed, and the crops were directly seeded into the previous crop's residue.

No-till plus cover crops includes the addition of a winter rye crop planted in between main crops and allowed to overwinter. The cover crop was planted 7 days after the main crop's harvest and was terminated 7 days prior to the main crop's planting. The cover crop residue was left in the field.

Intermittent tillage scenarios are when the tillage management changes per year. Intermittent tillage with intensive tillage was defined as no-till followed by intensive tillage in alternating years. Similarly, intermittent tillage with reduced tillage was defined as no-till followed by reduced tillage in alternating years. For the corn-soybean crop rotation with intermittent tillage, the corn years received the no-till management.

Continuous Tillage Practices

A comparison between intensive tillage, reduced tillage, no-till, and no-till plus cover crops shows significant effects on soil organic carbon (SOC). These tillage practices were simulated continuously for a 30-year period for both a monocropping corn system and a corn-soybean crop rotation.

Across 94 Major Land Resource Areas (MLRAs) in the Midwest and Eastern United States, the no-till plus cover crops scenario had the highest rate of increase in SOC, followed by no-till, reduced tillage, and then intensive tillage with the lowest rate of increase (Table 6.1, Figure 6.1). This pattern is consistent for both the monocropping corn system and the corn-soybean rotation.

The range and direction of the SOC stocks changes varied across the MLRAs. The spatial distribution of the rates of change in SOC is shown in Figure 6.2. The rates are affected significantly by both the biomass amounts returned to the soil and the soil type and associated initial SOC value prior to management changes. The upper Midwest U.S. show the highest emissions from SOC under intensive tillage management due to high initial SOC values. Figures 6.3 and 6.4 highlight how trends in SOC are influenced by location and initial SOC value. For site 1 in North Dakota, intensive tillage causes large losses in SOC, while reduced tillage has lower emissions from SOC. Both no-till and no-till plus cover crop scenarios cause very slight gains in SOC. However, for site 2 in Nebraska, there is a clear gain in SOC with the no-till plus cover crop scenario. For site 3 in Illinois, the initial SOC value is low and adding residues to the soil causes an increase in SOC. Site 4 in Pennsylvania also shows increases in SOC across all management scenarios, but to a lesser extent than site 3.

Table 6.1. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for varying management scenarios for 94 MLRAs, showing the mean and range across MLRAs.

Management Scenario	Average Change in Soil Organic Carbon (kg ha-1 yr-1) for 94 MLRAs			
	Monocropping Corn System		Corn-Soybean Rotation	
	mean	range	mean	range
Intensive Tillage	212	-452 to 762	2	-629 to 559
Reduced Tillage	242	-310 to 604	207	-213 to 678
No-Till	305	-54 to 646	318	-30 to 631
No-Till + Cover Crops	409	61 to 696	459	78 to 727

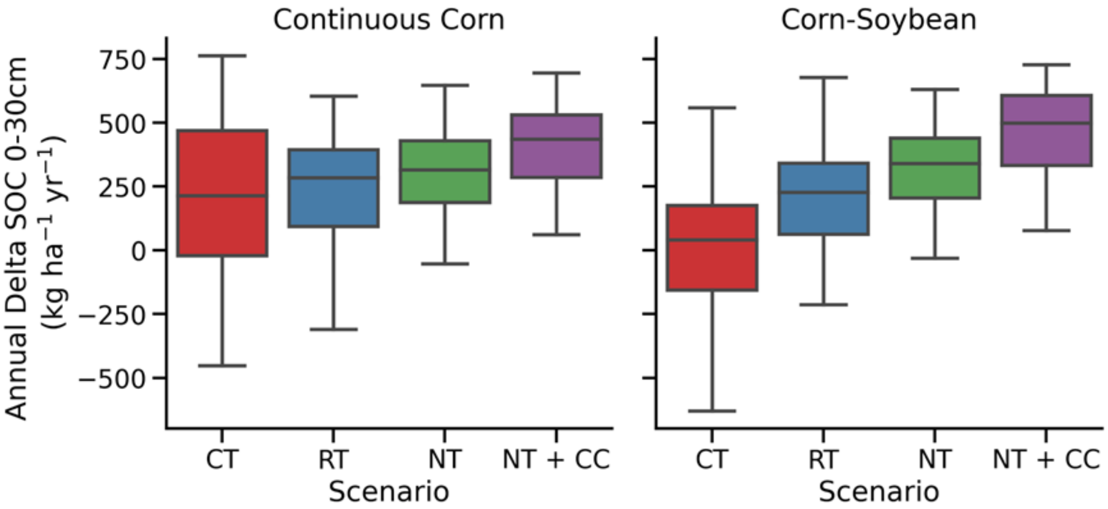


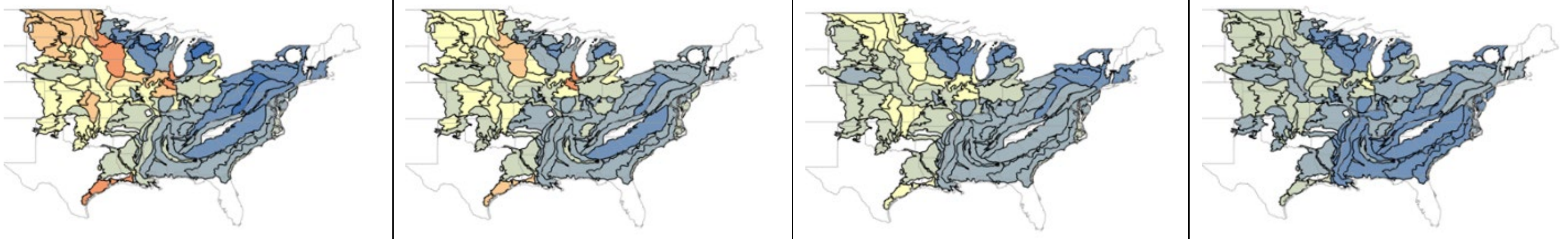
Figure 6.1. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for varying management scenarios for 94 MLRAs, where CT is intensive tillage (also referred to as intensive tillage), RT is reduced tillage, NT is no-till, and NT + CC is no-till with cover crop. The box extends from the first to third quartile of the data, with a line at the median, and the whiskers extend to the 1.5x the inter-quartile rage from the box.

a) Intensive Tillage, Continuous Corn

b) Reduced Tillage, Continuous Corn

c) No-till, Continuous Corn

d) No-till + Cover Crop, Continuous Corn



e) Intensive Tillage, Corn-Soybean Rotation

f) Reduced Tillage, Corn-Soybean Rotation

g) No-till, Corn-Soybean Rotation

h) No-till + Cover Crop, Corn-Soybean Rotation

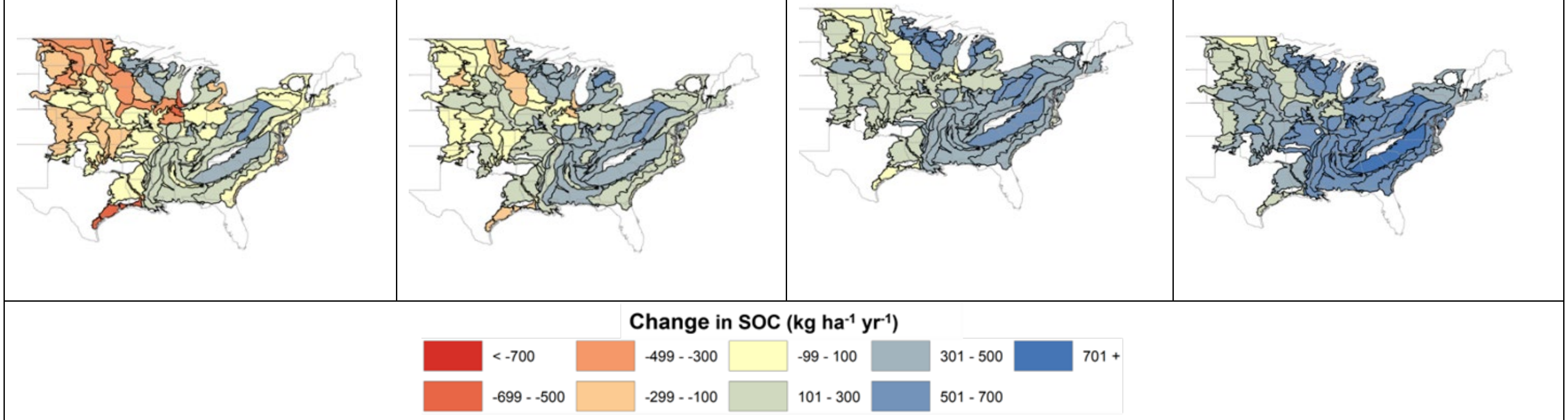


Figure 6.2. Maps of average change in SOC per year (kg ha^{-1} yr^{-1}) for each MLRA region outlined in black. The U.S. states are outlined in gray. The top row shows the continuous corn scenarios and the bottom row shows the corn-soybean rotation scenarios. The columns indicate a varying management: intensive tillage (also referred to as conventional tillage), reduced tillage, no-till, and no-till plus cover crop.

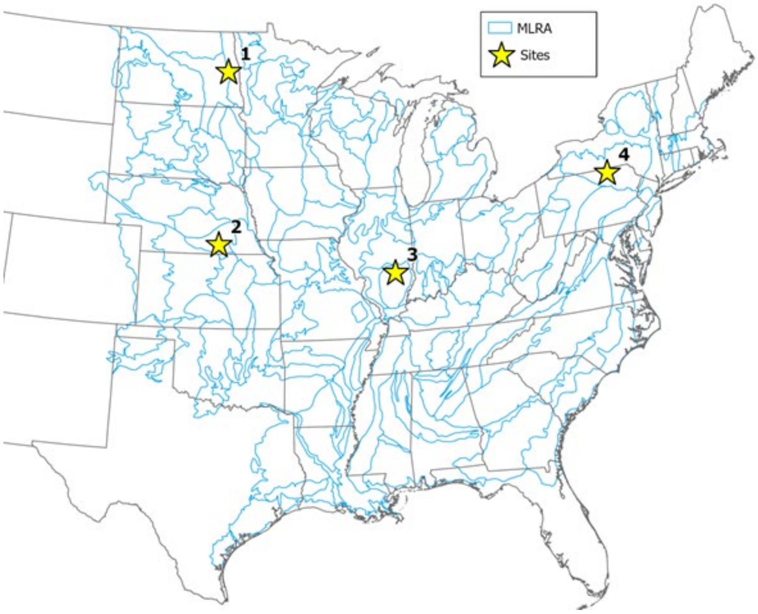


Figure 6.3. Locations of selected 4 example sites, with site 1 located in North Dakota, site 2 in Nebraska, site 3 in Illinois, and site 4 in Pennsylvania these sites illustrate the variability in baseline emissions and sequestration.

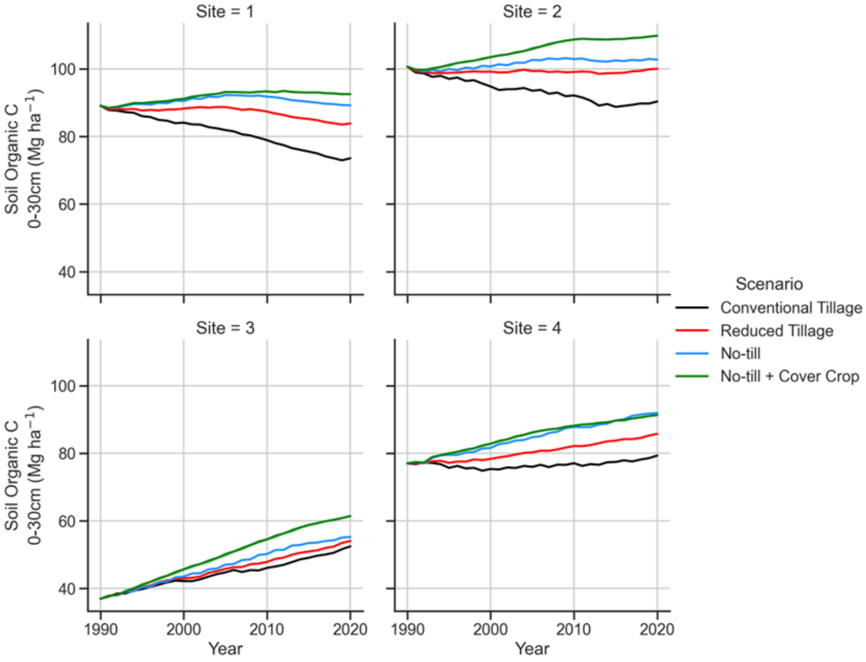


Figure 6.4. Annual timeseries of SOC (Mg ha^{-1}) for 4 sites with intensive tillage (also referred to as conventional tillage), reduced tillage, no-till, and no-till plus cover crop management under a corn-soybean rotation.

Intermittent Tillage Practices

Intermittent tillage practices over a 30-year period, alternating between tillage and no-till management, showed a higher rate of increase in SOC than continuous tillage (Table 6.2, Figure 6.5).

It is difficult to separate the effects of individual years on SOC because the returned crop residues of the previous crop and the tillage of the current crop affect SOC within the same year. We analyzed the change in SOC between harvest dates to attempt to allocate SOC changes between the no-till and tillage years.

For intermittent tillage with reduced tillage within the monocropping corn system, in years of no-till corn, the rate of SOC was 319 kg ha^{-1} yr^{-1} and in years with reduced tillage, the rate of SOC was 345 kg ha^{-1} yr^{-1}. For the corn-soybean rotation, in years of no-till corn, the rate of SOC was 373 kg ha^{-1} yr^{-1} and in soybean years with reduced tillage, the rate was 281 kg ha^{-1} yr^{-1}.

Table 6.2. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for intermittent tillage scenarios for 94 MLRAs, showing the mean and range across MLRAs.

Management Scenario	Average Change in Soil Organic Carbon (kg ha^{-1} yr^{-1}) for 94 MLRAs			
	Monocropping Corn System		Corn-Soybean Rotation	
	mean	range	mean	range
Intermittent No-Till + Intensive Tillage	314	-353 to 772	197	-303 to 670
Intermittent No-Till + Reduced Tillage	332	-193 to 665	327	-77 to 700

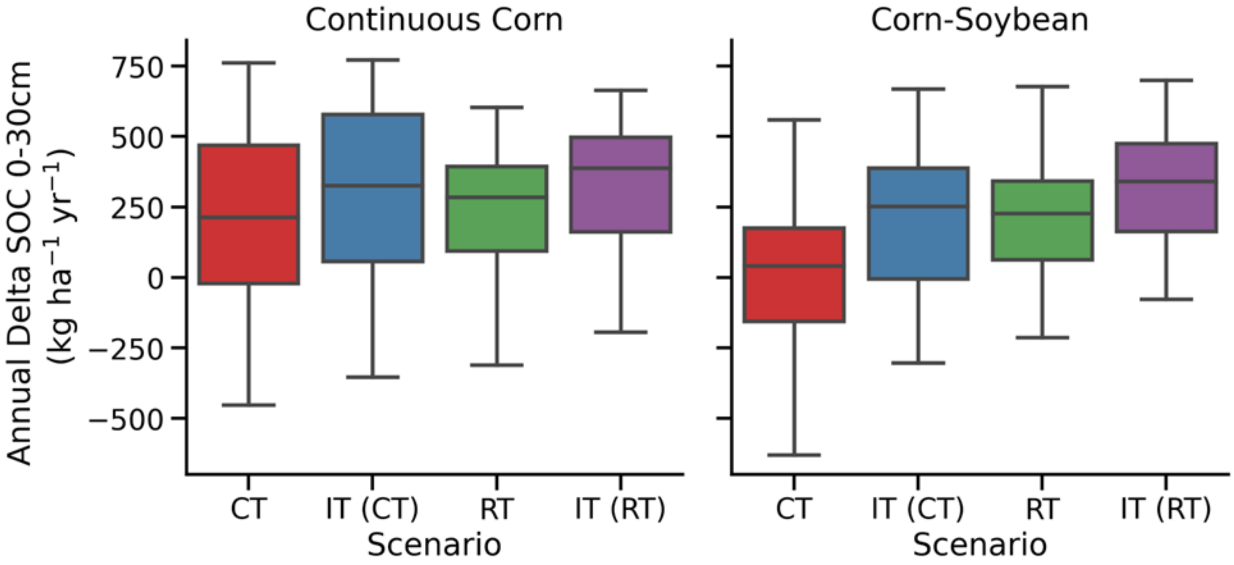


Figure 6.5. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for intermittent tillage scenarios for 94 MLRAs, where CT is intensive tillage (also referred to as conventional tillage), IT (CT) is intermittent tillage with intensive tillage (also referred to as conventional tillage), RT

is reduced tillage, and IT (RT) is intermittent tillage with reduced tillage. The box extends from the first to third quartile of the data, with a line at the median, and the whiskers extend to the 1.5x the inter-quartile rage from the box.

Extreme case of 3 years of no-till followed by intensive tillage

In the extreme scenario of 3 years of no-till followed by a complete reversion to tillage, the rates of change in SOC after 30 years are very similar to the continuous tillage scenarios (Table 6.3, Figure 6.6) as would be expected given that conventional practices are deployed 90% of the time. However, a significant portion of the carbon stock changes associated with the initial 3 years of alternative management are retained and are reflected in the outcomes after 30 years.

For the scenario with 3 years of no-till followed by reduced tillage, in the continuous corn system the 3 years of no-till had an average rate of 265 kg ha^{-1} yr^{-1} of SOC and for years with reduced tillage the rate was 209 kg ha^{-1} yr^{-1}. For the corn-soybean rotation, the 3 years of no-till had a rate of 373 kg ha^{-1} yr^{-1} and for years with reduced tillage the rate of SOC was 238 kg ha^{-1} yr^{-1}.

Table 6.3. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for extreme management scenarios for 94 MLRAs, showing the mean and range across MLRAs.

Management Scenario	**Average Change in Soil Organic Carbon (kg ha^{-1} yr^{-1}) for 94 MLRAs**			
	Monocropping Corn System		Corn-Soybean Rotation	
	mean	range	mean	range
No-Till for 3 years + Intensive Tillage	240	-403 to 792	25	-581 to 606
No-Till for 3 years + Reduced Tillage	252	-295 to 613	215	-205 to 687

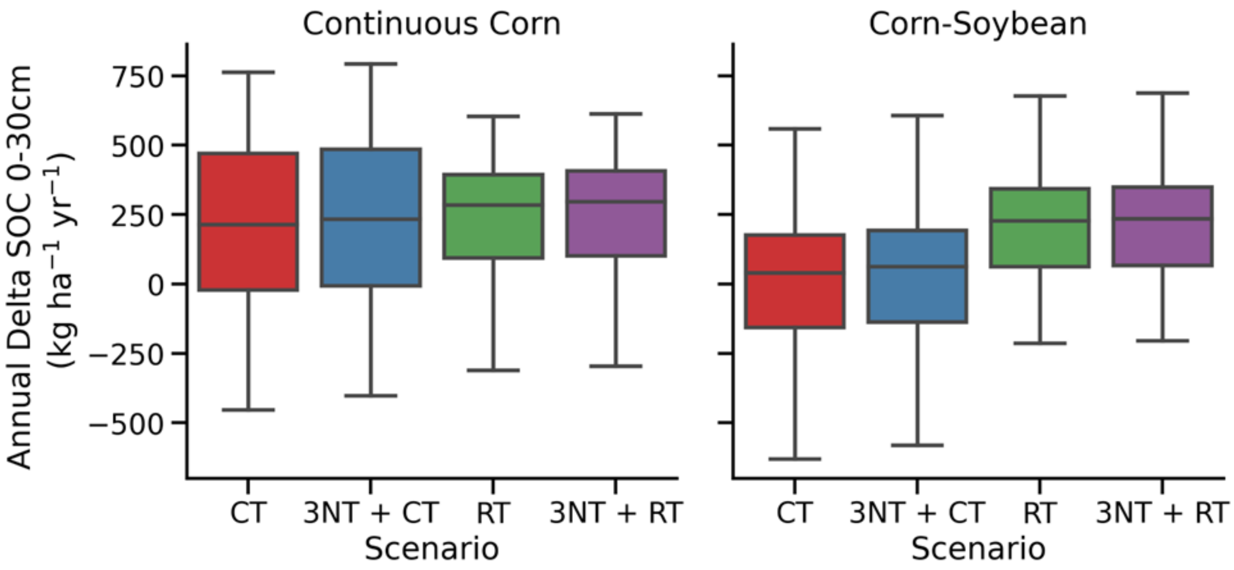


Figure 6.6. Average change in soil organic carbon per year (kg ha^{-1} yr^{-1}) for extreme management scenarios for 94 MLRAs, where CT is intensive tillage (also referred to as conventional tillage), 3NT + CT is 3 years of no-till followed by intensive tillage (also referred to as conventional tillage), RT is reduced tillage, and 3NT + RT is 3 years of no-till followed by reduced tillage. The box extends from the first to third quartile of the data, with a line at the median, and the whiskers extend to the 1.5x the inter-quartile rage from the box.

The change in SOC was calculated as the average of the yearly rates of change in SOC for the 0-30cm layer for each MLRA.

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