Impacts of Nitrogen Fertilization and Conservation Tillage on the Agricultural Soils of the United States: A Review

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Abstract

This review evaluated the effects of nitrogen (N) fertilization and conservation tillage systems on SOC stocks. N fertilizer additions had significant positive impact on SOC content, but the magnitude of this effect differed as a result of varying cropping systems: as cropping intensity increased, measured SOC content between fertilized and control treatment also increased. Significant differences of measured SOC stocks were detected between no till and conventional till, as well as reduced till and conventional till. However, no significant difference was observed between reduced till and no till. The differences of measured SOC content between no till and conventional till appeared to be significantly associated with treatment duration. Crop rotation system, soil texture, and mean annual precipitation did not have significant effects on SOC stocks produced from conventional tillage to no till. The results of this study confirmed that adoption of N fertilizer additions and conservational tillage systems can contribute to increased SOC level and thereby have the potential to mitigate the enhanced greenhouse gas effect. However, the evaluation of net carbon dioxide mitigation potential of these two recommended management practices should be carried out under a full carbon cycle analysis from carbon input to carbon output.

Keywords: soil organic carbon, nitrogen fertilization, no till, conventional till, agricultural productivity

1. Introduction

Modern agricultural practices, both agricultural extensification and intensification, have widespread negative environmental impacts such as biodiversity loss, damage to the environment, and degradation of critical ecosystem services [1]. Global climate change has been considered as one of the most pressing challenges that humans face in the 21st century [2]. As one of the major greenhouse gases (GHG), atmospheric CO_2 contributes substantially to global climate change. Since the industrial revolution, CO_2 concentration in the atmosphere has increased from 280 ppmv (parts per million by volume) to 391 ppmv in 2011 [3]. In Europe, agricultural land use has been estimated to be the largest biospheric source of carbon emission, with a total carbon loss of 300 Mt C yr^{-1} (Mt C = million tons of carbon) [4].

As one of the main options to mitigate global climate change, carbon sequestration can remove CO_2 by transferring CO_2 from the atmosphere to the terrestrial biosphere [5, 6]. Terrestrial ecosystems can sequester CO_2 through photosynthesis and store or release carbon in four fundamental carbon pools (reservoirs with the capacity to store and release carbon) including aboveground biomass, belowground biomass, soil, and dead organic matter. Soil is the largest terrestrial carbon pool, which includes two major components: soil organic carbon (SOC) and soil inorganic carbon (SIC). However, most studies have been focused on SOC because SOC is the main component in most terrestrial ecosystems, and because SOC is the key factor of soil fertility and vegetation production [7]. According to the Intergovernmental Panel on Climate Change (IPCC) report, the terrestrial SOC contains about two times the amount of carbon stored in the atmosphere and vegetation [2].

Depending on land use and management practices, agricultural soils can act as a potential sink or source for atmospheric CO_2 [8–10]. Land conversions from natural to agricultural ecosystems can release large amounts of carbon [11]. It has been estimated that 50% of SOC in the top 20 cm depth of soil and 25–30% in the top 100 cm depth can be released following 30–50 years of land conversion to agriculture [12–14]. Agricultural cultivation of soil by plowing or other conventional tillage methods can also release CO_2 into the atmosphere, causing the decline of SOC pool [15]. With increasing demand for food and other living resources, agricultural intensification is generally seen as a necessary step to meet the joint food and environmental challenges [1]. Therefore, the way in which we design agricultural management practices has been considered as one of the most important strategies when trying to combat global climate change [14].

Recommended management practices (RMPs) are suggested as one of the principal ways in promoting SOC sequestration in agricultural soils [16]. By adopting RMPs, global SOC sequestration was estimated to vary from 0.4 to 0.8 Pg C yr^{-1}, which accounted for 33–100% of the total SOC sequestration potential in the world [17]. Some studies have reviewed the effects of different agricultural management practices on SOC stocks [8, 13, 16, 18–21]. Lal et al. [16] showed that if land management practice was designed properly, U.S. agricultural lands can be a major sink for carbon sequestration with the total carbon sequestration potential of 75–208 MMt C yr^{-1} (MMt C = million metric tons of carbon). West and Marland [20] used a full carbon cycle analysis (calculates both carbon input and carbon output) to compare carbon sequestration, carbon emissions, and net carbon flux associated with various tillage practices in the United States. VandenBygaart et al. [21] reviewed long-term studies in Canada to assess the influence of different management practices on SOC stocks. Estimates and uncertainties of the changes in SOC stock were compiled and utilized to estimate CO_2 emissions from agricultural soils around the world.

Among all RMPs, nitrogen (N) fertilization management and conservation tillage systems are two of the most highly recommended management practices in increasing SOC stocks in

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the agricultural soils, therefore having the potential to reduce the net CO_2 emissions into the atmosphere [22–25]. The major mechanism of N fertilizer addition in increasing SOC storage is through increases in crop yield and biomass production. In turn, more crop residues could be returned to the soil. In fact, the amount of crop residues returned to the soil is positively related to the amount of carbon sequestered [26–28]. Nonetheless, nitrogen fertilization's effect on SOC concentration varies among site-specific management, soil type, and climatic conditions [29, 30].

By definition, conservation tillage is any system that maintains at least 30% of crop residue on the soil surface with minimum or no tillage [31, 32]. The impact of various tillage systems on SOC content has been studied widely in field experiments. Lal et al. [9] reported a SOC sequestration potential of 24–40 Mt C yr^{-1} if adopting conservation tillage in the agricultural soils of the United States. No-till was estimated to emit less CO_2 (137 kg C ha^{-1}) than conventional tillage (168 kg C ha^{-1}), indicating that management practice from conventional tillage to no-till can enhance carbon sequestration [22]. No till often means more plant residue on the soil surface and less water and energy exchange between soil surface and the atmosphere. Hence, no till creates a system that favors SOC accumulation [33]. There are variations in the amount of carbon sequestration by no till practices due to differences in practice duration, climate conditions, soil types, crop rotation intensity, and management factors [32].

Several field studies have reported SOC stock changes as a result of nitrogen fertilization or conservation tillage management; however, data from such studies only provide site-specific examples of management impacts [30]. To gain a better understanding of management impacts on SOC stocks, a meta-analysis that compares and integrates the results from multiple studies is required [34]. There are several field studies that look at the effect of land management practices on SOC stocks since 2000. But there is no recent review after 2000. Therefore, a synthesis of studies published since 2000 will add new evidence to the effect of land management practices on SOC stocks. Furthermore, many of the recent reviews estimating carbon sequestration potential of cropland management practices have focused on European studies and little work has been done on the U.S. context. Another limitation in some of the reviews that examined management effects on SOC content is often based on studies that measure SOC stocks changes in the surface soil (<30 cm) [25]. For example, Baker et al. [35] criticized that higher SOC stocks as a result of no-till systems were almost always associated with soil samples collected above 30 cm. Therefore, a critical review that considers soil depth is very much needed to help validate no-till effects on SOC accumulation [36]. To my knowledge, such study is generally lacking.

The objective of this paper is to quantify the effects of N fertilization and conversion of management practice from conventional tillage (CT) to no till (NT) on soil organic carbon stocks in the United States. This will be accomplished by compiling available long-term experimental data from peer-reviewed journals. More specifically, the major goals of this review are twofold: (1) analyze the effects of N fertilization and tillage systems on SOC stocks, respectively, and (2) determine the main factors that can affect the response of SOC content to N fertilization and contrasting tillage systems.

2. Methods

2.1. Data sources and calculations

I used Google Scholar and Web of Science to search peer-reviewed literature between 2000 and 2014 with the keywords “nitrogen fertilization,” “till or tillage,” “soil organic carbon,” “management practices* soil carbon.” Studies on the effect of nitrogen fertilization and tillage systems on SOC stocks from literature search were filtered to include only studies carried out in the agricultural soils of the conterminous United States. Any study included in the analysis had to meet the following criteria: (1) experiment set-up in the field had to be clearly stated, including the start and end dates of the study or duration of the treatment, soil sampling depth, the amount of nitrogen fertilizer applied in the field over time, tillage system used, etc. (2) SOC stocks per unit area or SOC concentrations and soil bulk density had to be reported. (3) Changes in SOC stocks or SOC concentrations and soil bulk density had to be attributed to different nitrogen application rates or to contrasting tillage systems. (4) No crop residue removal should have occurred over the study period.

Data from reviewed papers were extracted. For fertilizer and tillage experiments, a control treatment is contrasted with an alternative treatment. For fertilizer experiments, I compared unfertilized (control) treatment with fertilized. There were 145 paired comparisons of measured SOC stocks between fertilized and control treatments. For tillage experiments, there were a total of 187 paired comparisons with contrasting tillage system: no tillage management was practiced in 186 paired-experiments, conventional tillage was practiced in 187 paired-experiments, and reduced till was applied in 38 paired-experiments. The key independent variable, total nitrogen applied, was calculated by adding up the amount of nitrogen fertilizer applied each year over the study period. For some studies, nitrogen application was not applied at a constant rate; then, the total amount of nitrogen fertilizer applied was calculated by adding up the actual application rate across the duration of experiment. Otherwise, total nitrogen applied was calculated by multiplying nitrogen fertilizer rate per year with treatment durations. The response variable, paired log difference of SOC measurement between fertilized and unfertilized/control practices, was calculated using Eq. (1), and was used to eliminate the differences of means and variances among different studies. In this particular case, if the response ratio is greater than zero, management practice from fertilized to unfertilized treatment increases SOC stocks.

$$\ln\ (\text{fertilized}) - \ln\ (\text{control}) = \ln\ (\text{fertilized}/\text{control}) \tag{1}$$

For tillage analysis, three principal tillage systems were considered: conventional tillage (CT), reduced till (RT), and no till (NT) (in some studies, no till treatment was set up as conservation tillage). The response variables, paired log difference between no till and conventional till, no till and reduced till, reduced till and conventional till, were calculated using Eqs. (2)–(4). Here, if the response ratio, ln (NT/CT), is greater than zero, no till is said to increase SOC stocks compared with conventional tilled system. Similarly, if response ratios, ln (NT/RT) and ln (RT/CT), are greater than zero, SOC stocks increase when changing from no till to reduced till, reduced till to conventional till, respectively.

$$\ln\ (\mathrm{NT}) - \ln\ (\mathrm{CT}) = \ln\ (\mathrm{NT/CT}) \tag{2}$$

$$\ln\ (\mathrm{NT}) - \ln\ (\mathrm{RT}) = \ln\ (\mathrm{NT/RT}) \tag{3}$$

$$\ln\ (\mathrm{RT}) - \ln\ (\mathrm{CT}) = \ln\ (\mathrm{RT/CT}) \tag{4}$$

Some studies in my dataset only reported SOC concentration and soil bulk density instead of total SOC stock. In that case, SOC stock was calculated as follows (Eq. (5)):

$$\mathrm{SOC}\ \left(\mathrm{Mg\ C\ ha^{-1}}\right) = \mathrm{SOC}\ (\%)^{*}\ \text{Soil bulk density}\ \left(\mathrm{Mg/m^3}\right)^{*}\ \text{Soil sampling depth (cm)} \tag{5}$$

The following were considered environmental and edaphic variables: experimental site, treatment duration (time since practice), crop rotation system, cropping index, soil sampling depth, soil texture, mean annual temperature (MAT), and mean annual precipitation (MAP). Based on crop rotation system, a discrete cropping index was calculated by incorporating the number of crops rotated per year, and the percentage of corn in the cropping system (after Alvarez [30]). The calculation of cropping index was also based on two assumptions: (1) residue produced from corn was twice as much as from other crops, and (2) two crops per year produced twice the amount of residue of one crop per year [24, 30]. Soil texture was categorized into three types: fine, loamy, and coarse. In terms of climatic data, MAT and MAP were extracted from the reviewed papers. If for any reason, MAT and MAP were not reported or missing from the study, they were estimated from the following website: http://www.ncdc.noaa.gov/.

2.2. Statistical analysis

2.2.1. Analysis of nitrogen fertilization and SOC stocks

First, a paired t-test was used to test whether SOC stock with fertilizer is significantly different from SOC without fertilizer (control). This was done by testing changes in measured SOC between fertilized and control treatments against zero at a significance level of 0.05. Then, bivariate and multivariate regression models were developed to investigate the relationship between paired log difference of measured SOC stocks (ln (fertilized/control)) and total nitrogen applied in a context shaped by variables that can moderate the effect of fertilization on SOC stock. Here, experimental location as random effect was combined with multivariate regression model because more than one measurement was taken from the same geographic location. Location as random effect relaxes the assumption that data of different plots with alternative treatments taken from the same site are independent from each other. Variables considered in the model include treatment duration, cropping index, soil sampling depth, soil texture, mean annual temperature, and mean annual precipitation. Finally, paired log difference of measured SOC stocks between fertilized and control treatment was further analyzed for the effects of relevant environmental and edaphic variables (e.g., soil texture). Means and 95% confidence intervals (CIs) of paired log difference in measured SOC across the dataset were reported. If the 95% CIs of paired log difference in measured SOC stocks for a given variable does not overlap with zero, the response of that variable to fertilizer effect is said to be significantly different from the control [34].

2.2.2. Analysis of tillage systems and SOC stocks

Paired t-tests were first conducted to compare the effects of contrasting tillage systems (no till vs. conventional till, no till vs. reduced till, and reduced till vs. conventional till) on SOC stocks at a significance level of 0.05. Linear and curvilinear models were tested to see which model fits better with the dataset. Linear regression model was therefore chosen for this analysis. I estimated the correlation between treatment duration and paired log difference in measured SOC produced from fertilizer. Multivariate regression model was also applied to develop equations that explain the effects of no tillage system on SOC stocks with control variables that can potentially affect its response. Location as random effect model was also incorporated in the multivariate regression model with the same process that was applied in fertilizer experiments. Lastly, the effects of relevant environmental and edaphic variables on paired log difference of measured SOC between no till and conventional till was further analyzed with the mean and 95% CIs calculated. All statistical analyses were performed in the Stata software package (StataCorp. 2013. Stata Statistical Software: Release 13. College Station, TX: StataCorp LP).

3. Results and discussion

3.1. Analysis of nitrogen fertilization and SOC stocks

A total of 145 paired experiments with varying nitrogen fertilization rates were compiled in the database for this analysis (**Table 1**). The database covers 10 states. Of all the 145-paired studies, the total nitrogen fertilization applied varied from 0.089 to 6.44 Mg N ha^{-1}. Changes of SOC stock produced from varying nitrogen fertilization treatments were between −14 and 22 Mg C ha^{-1}, with an average of 2.32 Mg C ha^{-1}. The treatment durations of these experiments were between 2 and 27 years, with an average of 10.8 years. The soil sampling depth spanned a wide range from 7.6 to 120 cm, with an average of 48.4 cm. In terms of weather attributes, the lowest and highest mean annual temperatures were 7 and 17°C, averaging 11.4°C. The mean annual precipitation ranged from 357 to 1400 mm at an average of 762.7 mm.

A paired t-test showed that measured SOC under fertilizer treatments was significantly different ($p < 0.001$, $t = 5.74$, degrees of freedom = 144) from measured SOC under control treatments.

Description	Mean	Std	Min	Max	# of observations
Total nitrogen applied (Mg N ha^{-1})	0.99	0.89	0.089	6.44	145
ln (fertilized/control)	0.03	0.06	−0.165	0.28	145
Treatment duration (years)	10.8	6.6	2	27	145
Soil sampling depth (cm)	48.4	35.7	7.6	120	145
Mean annual temperature (°C)	11.4	3.4	7	17	145
Mean annual precipitation (mm)	763	300	357	1400	145

Table 1. Summary statistics for the paired data of N fertilizer experiments used in this study.

Roughly 66% (n = 95) of the total observations showed the positive effect of nitrogen fertilizer on SOC storage with no crop residue removal, whereas about 32% (n = 47) and 2% (n = 3) showed negative and no correlation between total nitrogen fertilization and SOC content, respectively. When total nitrogen fertilization rate is higher than 3.51 Mg ha^{-1}, no SOC depletion occurred (**Figure 1**). Total nitrogen applied had a significant positive impact on measured SOC change between fertilized and control treatment ($p < 0.001$) (**Figure 1**). As the application of total nitrogen fertilizer increased, the paired log differences of measured SOC stocks between fertilized and control treatments increased. Specifically, when total nitrogen fertilizer increased by 1 Mg ha^{-1}, the paired log differences of measured SOC stocks increased by 0.02. Measured SOC stock increased by 2% relative to control treatment.

The increases in SOC level as a result of N fertilizer addition are attributable to the increases in net primary productivity and residue-C input [37]. A strong negative correlation between SOC content and crop residue production was observed under N deficit by Campbell and Zentner [38, 39]. The significant positive effect of N additions on SOC level detected agrees with a review by West and Post [22] based on a compiled global database of 67 long-term agricultural experiments. However, the magnitude of this effect varied from significant increase [40–45] to only mild increase in the level of SOC [46–49].

In this study, the effect of N additions on measured SOC stocks was, however, moderated by the relevant environmental and edaphic characteristics, including cropping index, soil sampling depth, soil texture index, mean annual temperature (MAT), and mean annual precipitation (MAP). Here, a multivariate regression model (Eq. (6)) with random effect was developed to characterize the relationship between paired log differences of measured SOC stocks (ln (fertilized/control)) and the total nitrogen applied in the experiment (**Table 2**).

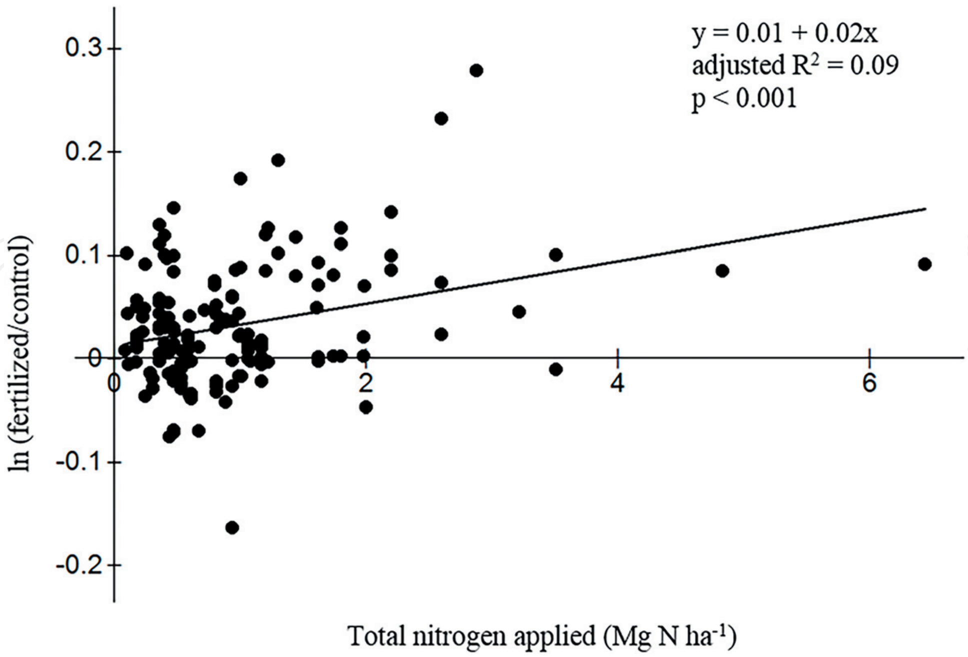

Figure 1. Paired log difference of soil organic carbon between fertilized and control measurement (ln (fertilized/control)) plotted against the total nitrogen applied in experiments with no crop residue removal.

Dependent variable	ln (fertilized/control)
Total nitrogen applied	0.013** [2.120]
Cropping index	0.063*** [4.513]
Soil sampling depth	−0.000 [−0.348]
Soil texture index	0.009 [0.700]
MAT (mean annual temperature)	−0.003 [−1.023]
MAP (mean annual precipitation)	−0.000 [−0.950]
Constant	−0.018 [−0.571]
Observations	145
Number of location	12

Table 2. This table presents multivariate regression results for relationship between paired log difference of soil organic carbon between fertilized and control measurement and the total nitrogen applied in experiments with no crop residue removal. The dependent variable is calculated as follows: ln (fertilized/control) = ln (fertilized) − ln (control). Independent variables are total nitrogen applied (Mg N ha^{-1}), cropping index, soil sampling depth, soil texture index (1 = fine, 2 = loamy, 3 = coarse), and climate condition including MAT (°C) (mean annual temperature) and MAP (mm) (mean annual precipitation). The t-values are given in brackets. ***, **, and * denote significance at the 0.01, 0.05, and 0.1 level, respectively.

$$\ln\ (\text{fertilized/control}) = -0.018 + 0.013\ \text{N} + 0.063\ \text{C}_\text{i} - 0.000\ \text{D} + 0.009\ \text{SI} - 0.003\ \text{T} - 0.000\ \text{P} \tag{6}$$

($p < 0.01$, number of observations = 145, number of locations = 12).

where N is the total nitrogen applied (Mg N ha^{-1}), C_i is the cropping index, D is the soil sampling depth (cm), SI is the soil texture index, T is the mean annual temperature (°C), and P is the mean annual precipitation (mm).

Cropping system significantly increased paired log difference of measured SOC stocks between fertilized and control treatment ($p < 0.01$; **Table 2**). When cropping index increased by 1, paired log difference of measured SOC stocks increased by 0.063. Measured SOC stock under fertilized treatment was 6.5% higher than SOC stock under control treatment. Increases in cropping index can be achieved by either rotating more crops per year or incorporating corn as the main component in the cropping system. By rotating more crops per year, net primary productivity of the cropland increased. Hence, SOC storage increased, therefore contributing to the absorption of the atmospheric carbon dioxide. Due to a large expansion in ethanol production in the United States, the market price of corn has experienced significant overall increases in recent years. Response to high corn prices, farmers increasingly choose to increase corn acreage at the expense of other crops, such as soybean. Therefore, due to reduced soybean production, soybean price also increases significantly in recent years. These socioeconomic

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factors have induced a series of cropping system changes in the Midwest Corn Belt. Hence, cropping systems in the Midwest Corn Belt include three major types: continuous corn cropping, continuous soybean cropping, and corn-soybean/soybean-corn rotation.

SOC level under continuous corn is often higher than under corn-soybean/soybean-corn rotation because corn produces more biomass than soybean does [18, 37]. Measured SOC stocks increased significantly ($p < 0.001$, $t = 9.41$, degrees of freedom = 45) when cropping index equals 2 (**Figure 2**). More specifically, measured SOC stock with fertilizer increased by 18% compared with control treatment. One of the possible cropping system when the cropping index equals 2, is continuous corn cropping. West and Post [22] found that as rotation intensity increased, SOC sequestration rate increased by 200 ± 120 kg C ha^{-1} yr^{-1}, with an exception of change from continuous corn to corn-soybean/soybean-corn rotation. However, when cropping index is lower than 2, the effect of cropping index on changes of measured SOC stocks was not significantly different among cropping sequences.

There was no significant correlation between soil sampling depth and changes in measured SOC stocks produced by nitrogen fertilization application (**Table 2**). SOC stocks significantly increased among all soil sampling depths measured in 145-paired experiments (**Figure 3**). Means and 95% CIs of paired log differences of measured SOC stocks overlapped, which means that the N effect on SOC stocks did not differ across all sampling depths. Measured SOC increased profoundly (10%) when soil sampling depth was below 30 cm.

Soil texture includes three categories: fine (=1), loamy (=2), and coarse (=3). Here, the correlation between soil texture index and paired log difference of measured SOC stocks was not detected (**Table 2**). This contradicts with Alvarez [30] who observed a significant positive

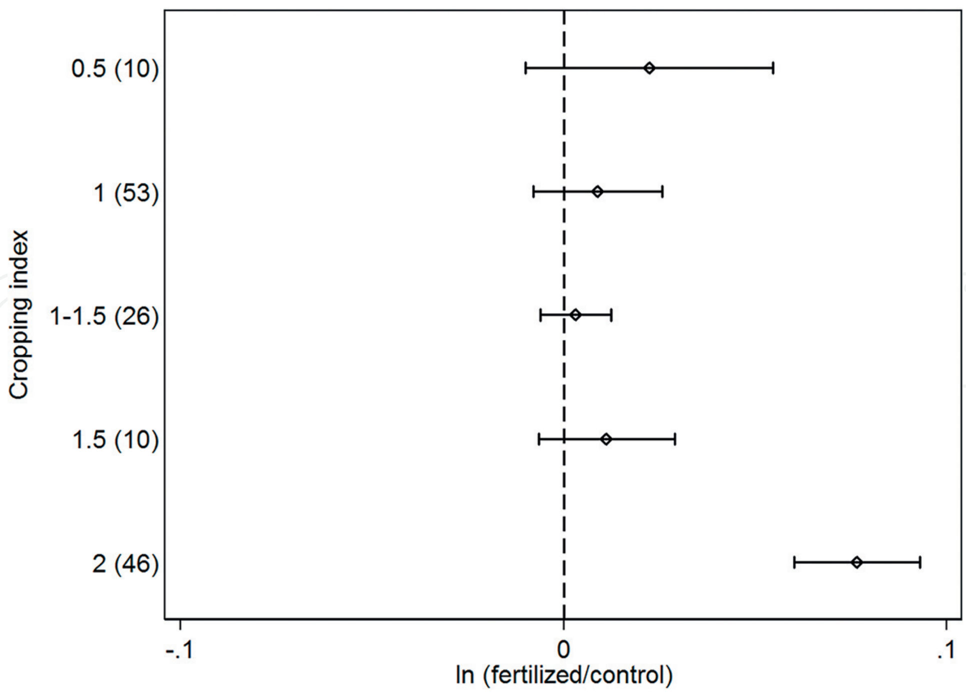

Figure 2. The effects of cropping index on paired log difference of soil organic carbon between fertilized and control measurement (95% confidence intervals are shown and numbers of observations are included in parentheses).

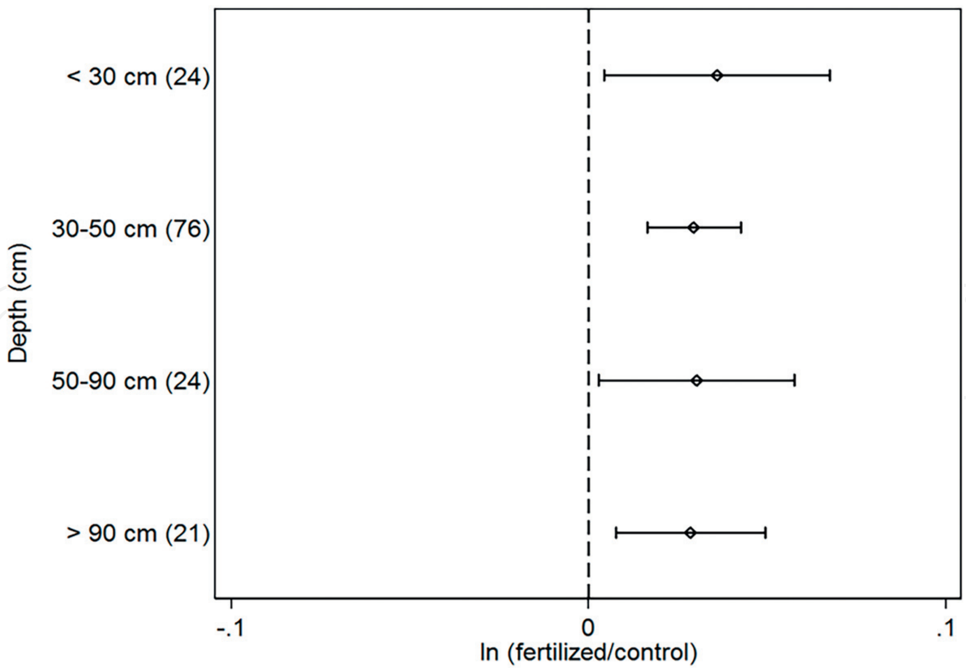

Figure 3. Paired log difference of soil organic carbon between fertilized and control measurement across the soil sampling depth (95% confidence intervals are shown and numbers of observations are included in parentheses).

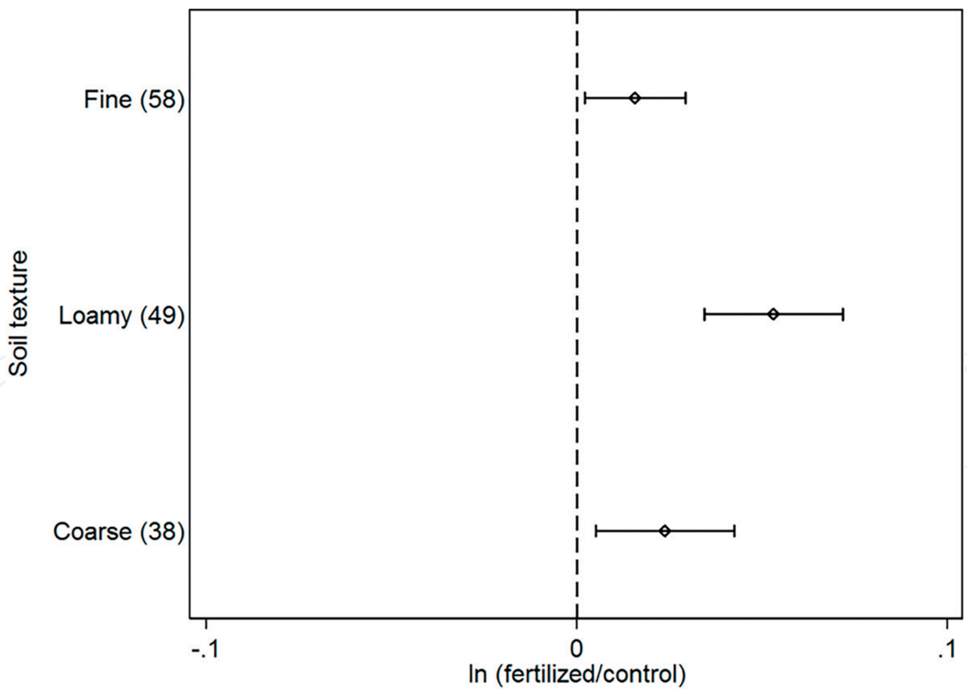

Figure 4. The effects of soil texture on paired log difference of soil organic carbon between fertilized and control measurement (95% confidence intervals are shown and numbers of observations are included in parentheses).

relationship between soil texture index and changes in SOC stocks. Coarse-textured soils are often associated with lower soil fertility; therefore, might response stronger to nitrogen fertilizer addition if other factors are held constant [30]. The effect of nitrogen fertilizer on SOC stocks was significant across all soil types in this analysis (**Figure 4**). In fact, areas with fine- and coarse-textured soils did not differ significantly in terms of their effects on measured SOC stocks. On average, soils with loamy texture significantly increased ($p < 0.0001$, $t = 5.71$, degrees of freedom = 48) SOC stocks by 13% than those of fine- (4.6%) and coarse-textured (6.9%) soils.

In terms of climates, no statistically significant correlation was found between mean annual temperature and paired log difference of measured SOC, mean annual precipitation and paired log difference of measured SOC, respectively (**Table 2**). Previous studies that examined relationship between climate conditions and N effect have come to mix conclusions. Parton et al. [50] reported that temperature can negatively affect residue-C transition to SOC stocks. Therefore, it is expected that the effect of nitrogen fertilization on SOC stocks is greater in temperate climates compared with tropical climates [30].

Furthermore, I found that areas with temperature < 12°C sequestered significantly more SOC, but not in areas with temperature ranging from 12 to 15°C (**Figure 5**). In fact, the highest SOC increase located in areas with temperature lower than 8°C (+15%). Increase in measured SOC was also significant in areas with temperature above 15°C. Considering distributions of measured SOC difference across areas with various mean annual precipitations, N fertilizer had a significant

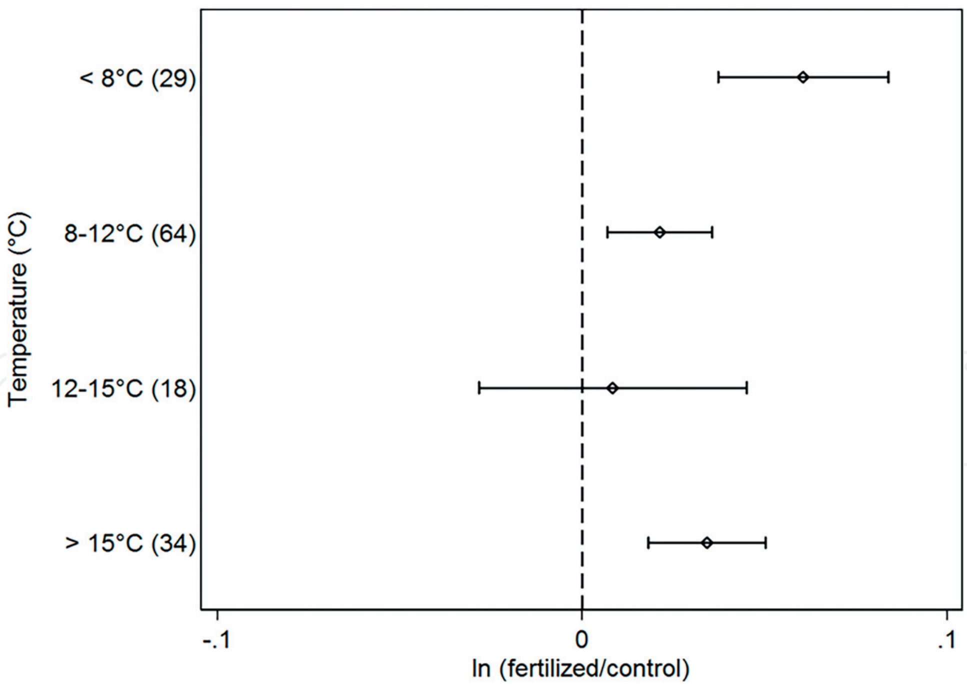

Figure 5. The effects of mean annual temperature on paired log difference of soil organic carbon between fertilized and control (95% confidence intervals are shown and numbers of observations are included in parentheses).

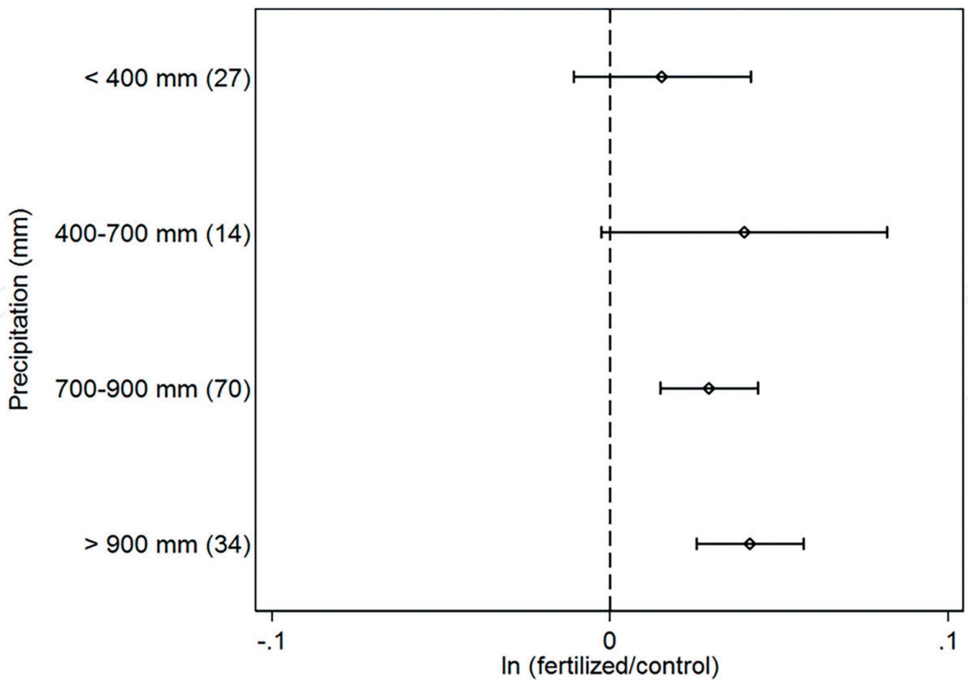

Figure 6. The effects of mean annual precipitation on paired log difference of soil organic carbon between fertilized and control measurement (95% confidence intervals are shown and numbers of observations are included in parentheses).

impact on SOC stocks in the higher rainfall (>700 mm) areas, but had no effect on SOC stocks in lower rainfall (<700 mm) areas (**Figure 6**).

Even though nitrogen fertilization can result in SOC sequestration, its potential to remove carbon from the atmosphere is still debatable and requires a comprehensive evaluation of the whole process from fertilizer manufacture to transportation, and finally to applications in the fields [22]. The production of N fertilizers involves energy input from fossil fuel combustion, which in turn leads to carbon emissions back into the atmosphere. There are also post-production carbon emissions from fertilizer packaging, transportation, and field application [51]. Average carbon emissions associated with the production and use of N fertilizers were estimated to be 1.2 Mg C Mg^{-1} N applied [22, 52]. In conclusion, to evaluate carbon mitigation potential of N fertilization management, a comprehensive assessment from N manufacture, delivery, to application is required.

3.2. Analysis of tillage systems and SOC stocks

Three tillage systems were considered in this analysis, which include no till (NT), reduced till (RT), and conventional till (CT). Overall, studies compiled in this database comprise 187-paired experiments. Of all 187 paired data, 186 cases (99%) report changes in SOC stocks between no till and conventional till, 37 cases (20%) measure ΔSOC stocks between no till and reduced till, and 38 cases (20%) for SOC stocks changes from reduced till to conventional till (**Table 3**). The database covers 20 states. Among all 186 paired comparisons, paired log difference of measured SOC from conventional tillage to no tillage ranged from −0.37 to 0.6, with an average of 0.089. In other words, changes in measured SOC with no till management

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Description	Mean	Std	Min	Max	# of observations
ln (NT/CT)	0.089	0.151	−0.366	0.6	186
ln (NT/RT)	0.007	0.147	−0.213	0.569	37
ln (RT/CT)	0.065	0.083	−0.107	0.272	38
Treatment duration (years)	12.84	10.19	2	45	187
Soil sampling depth (cm)	35.75	27.53	6	150	187
Mean annual temperature (°C)	13.3	4.43	5.5	23.5	187
Mean annual precipitation (mm)	945	324	305	1584	187

Table 3. Summary statistics for the paired data of tillage experiments used in this study.

ranged from −31% to +82% compared with conventional tillage system. Paired log difference of measured SOC from reduced tillage to no tillage varied from −0.21 to 0.57, with a mean of 0.007. This suggests that changes in measured SOC with no till practice can decrease up to 19% and increase as much as 77% relative to reduced tillage. Paired log difference of measured SOC content from conventional tillage to reduced tillage ranged from −0.11 to 0.27, averaging around 0.06. The differences of measured SOC level between reduced till and conventional till varied from −11% to +31%. Of all 187 paired comparisons, the treatment durations were from 2 to 45 years, with an average of 12.8 years. Soil depth sampled was in a range of 6–150 cm, with an average of 35.7 cm. Mean annual temperature was from 5.5 to 23.5°C at an average of 13.3°C, and mean annual precipitation ranged from 305 to 1584 mm, averaging 945 mm.

Of all 186 observations that measured changes in SOC storage between no till and conventional till, approximately 71% (n = 133) of the total observations, showed positive values. Of all 37 paired experiments that reported SOC differences between no till and reduced till, more than half of the total cases (57%; n = 21) showed negative results, with 16 (43%) cases showed positive values. In contrast, among all 38 studies that reported changes in measured SOC stocks from conventional till to reduced till, only 2 cases showed negative values, 6 cases were no change, and the remaining 30 cases (79%) were positive values. Paired t-tests showed significant differences in measured SOC stocks between no till and conventional till ($p < 0.001$, $t = 8.06$, degrees of freedom = 185), reduced till and conventional till ($p < 0.001$, $t = 4.83$, degrees of freedom = 37), respectively. SOC stocks under no till and reduced till were on average 9% and 7% greater than those of conventional till. However, paired t-tests showed no significant differences between no till and reduced till. This could be true or it could be due to the low number of observations for this measure.

No significant correlation between paired log difference of measured SOC content and duration time was detected between reduced till and conventional till. However, paired log difference of measured SOC between no till and reduced till was significantly dependent on time since management practice ($p < 0.001$; **Figure 7**). Again, due to its low number of observations (n = 37), I won't further analyze this measure in this study. As expected, the differences of measured SOC stock between no till and conventional till were also significantly dependent on length of time since conversion ($p < 0.001$; **Figure 7**). The longer the time in no till management, the greater the amount of SOC stocks compared to conventional tilled fields. More specifically,

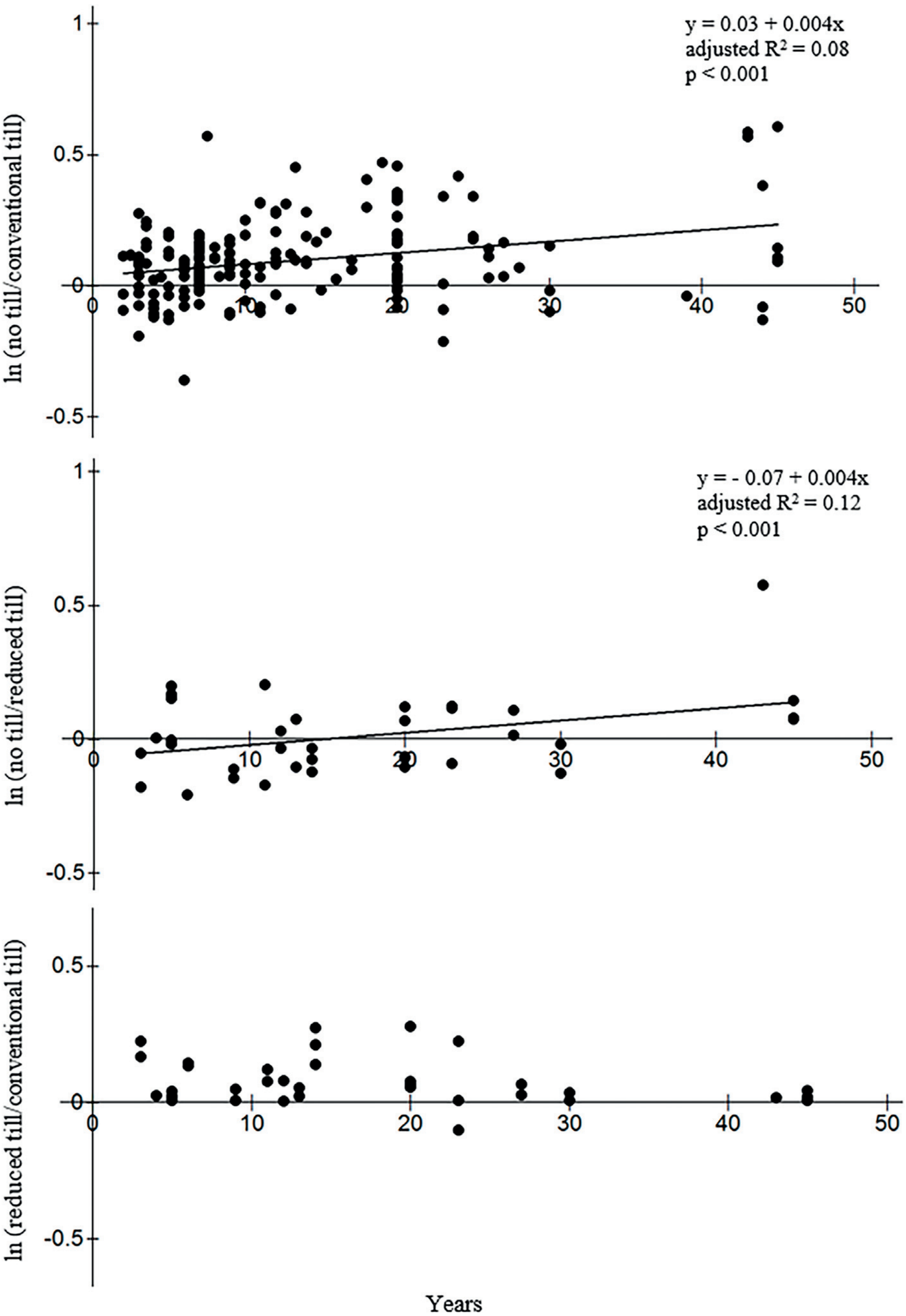

Figure 7. Paired log difference of soil organic carbon between contrasting tillage systems plotted against treatment durations. Here, tillage systems include no-till, conventional till, and reduced till.

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if treatment duration increases by 1 year, SOC stock would increase by 0.4% when changing from conventional tillage to no tillage system.

Increases in measured SOC stocks occurred in the soil when the duration of no tillage treatment was beyond 5 years (**Figure 8**). This result is consistent with the findings summarized by West and Post [22], that there was a delayed response of no till management on SOC stocks with peak sequestration rates in 5–10 years. Despite the high degree of variations in climate conditions, soil types, cropping systems, and other associated site characteristics, differences between conventional till and no till were still significantly ($p < 0.05$) time-dependent: SOC stock increased as the time in no-till management increased. A multivariate regression with random effects model (Eq. (7)) was established to account for the associated environmental and edaphic characteristics (**Table 4**).

$$\ln\ (\text{no till/conventional till}) = -0.157 + 0.004\ \text{DT} + 0.009\ \text{C}_i + 0.0001\ \text{D} + 0.038\ \text{SI} + 0.003\ \text{T} + 0.0001\ \text{P} \quad (7)$$

($p < 0.05$, number of observations = 186, number of locations = 70).

where DT is the treatment duration time (years), C_i is the cropping index, D is the soil sampling depth (cm), SI is the soil texture index, T is the mean annual temperature (°C), and P is the mean annual precipitation (mm).

There was no significant correlation between cropping system and changes in measured SOC stocks (**Table 4**). So did soil texture, mean annual temperature, and mean annual precipitation. Increases in measured SOC stocks occurred significantly when cropping index was greater than

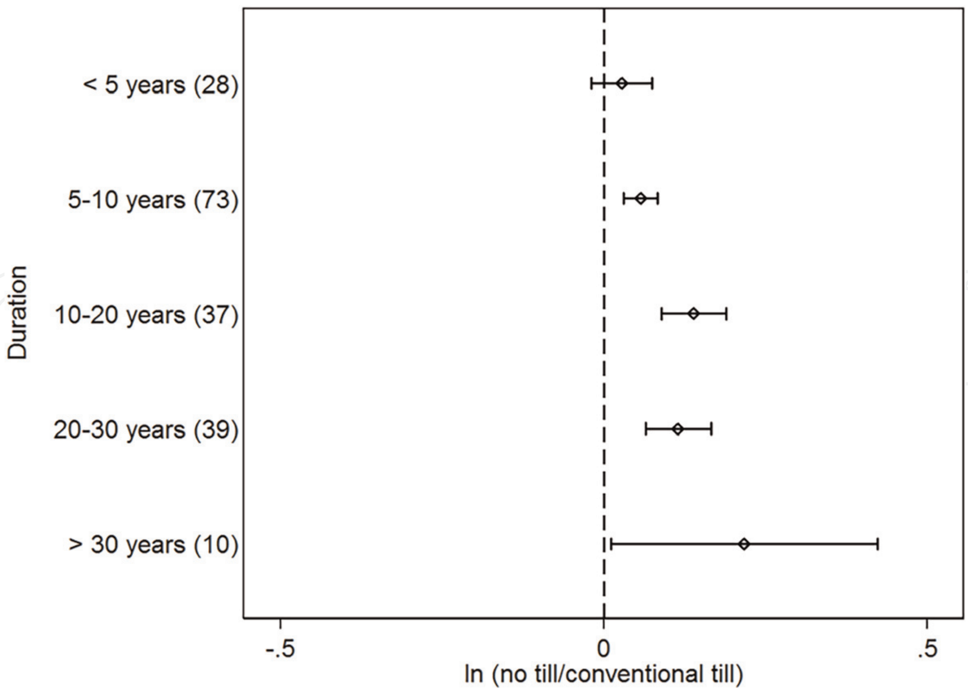

Figure 8. The effects of treatment durations on paired log difference of soil organic carbon measurement between no till and conventional till (95% confidence intervals are shown and numbers of observations are included in parentheses).

Dependent variable	ln (no till/conventional till)
Duration time	0.004** [2.431]
Cropping index	0.009 [1.140]
Soil sampling depth	0.0001 [0.228]
Soil texture index	0.038 [1.316]
MAT (mean annual temperature)	0.003 [0.703]
MAP (mean annual precipitation)	0.0001 [0.877]
Constant	−0.157* [−1.850]
Observations	186
Number of location	70

Table 4. This table presents multivariate regression results for relationship between paired log difference of soil organic carbon measurement from conventional till to no till and treatment duration. The dependent variable is calculated as follows: ln (no till/conventional till) = ln (no till) − ln (conventional till). Independent variables are treatment duration, cropping index, soil sampling depth, soil texture index (1 = fine, 2 = loamy, 3 = coarse), and climate condition including MAT (°C) (mean annual temperature) and MAP (mm) (mean annual precipitation). The t-values are given in brackets. ***, **, and * denote significance at the 0.01, 0.05, and 0.1 level, respectively.

0.5 (**Figure 9**). However, paired log differences of measured SOC between no till and conventional till were not significantly different from each other when cropping index was greater than 0.5. On average, SOC content from conventional tillage to no tillage increased by roughly 9% across all cropping sequences when cropping index was greater than 0.5. All three types of soil texture (fine, loamy, and coarse) had significant effects on measured SOC change from conventional till to no till (**Figure 10**). The conversion from conventional tillage to no tillage system had no effect on changes of measured SOC stocks in the lower rainfall (<900 mm) areas, but significantly increased measured SOC stocks in higher rainfall areas (>900 mm) (**Figure 11**).

There was no significant association between soil sampling depth and paired log difference of measured SOC stocks (**Table 4**). However, the distribution of paired log difference of measured SOC across all soil sampling depths showed significant ($p < 0.001$) increases in SOC content in the surface soil (<50 cm) and above 90 cm. In particular, increases in measured SOC stocks were greater (+34%) in the upper 30 cm of the soil profile relative to 30–50 cm of the soil profile. This result is consistent with previous studies.

Considering the distribution of paired log difference of measured SOC content across areas with different mean annual temperatures, there was no significant change in measured SOC level between no till and conventional till in areas with low temperature (<8°C). Areas with temperature above 8°C can significantly increase measured SOC stocks when applying no tillage system (**Figure 12**).

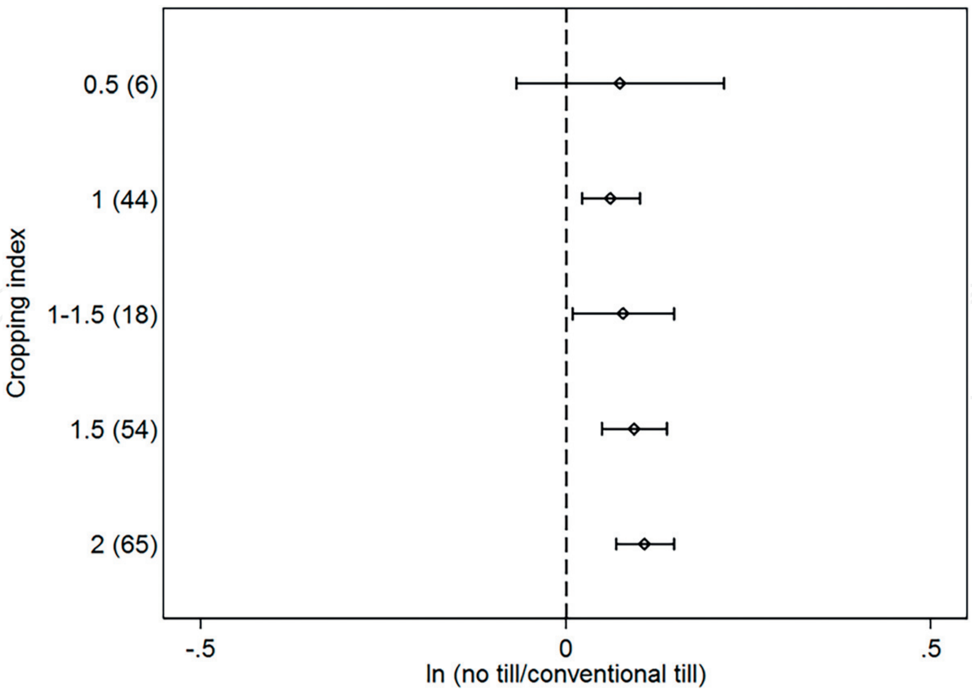

Figure 9. The effects of cropping index on paired log difference of soil organic carbon measurement between no till and conventional till (95% confidence intervals are shown and numbers of observations are included in parentheses).

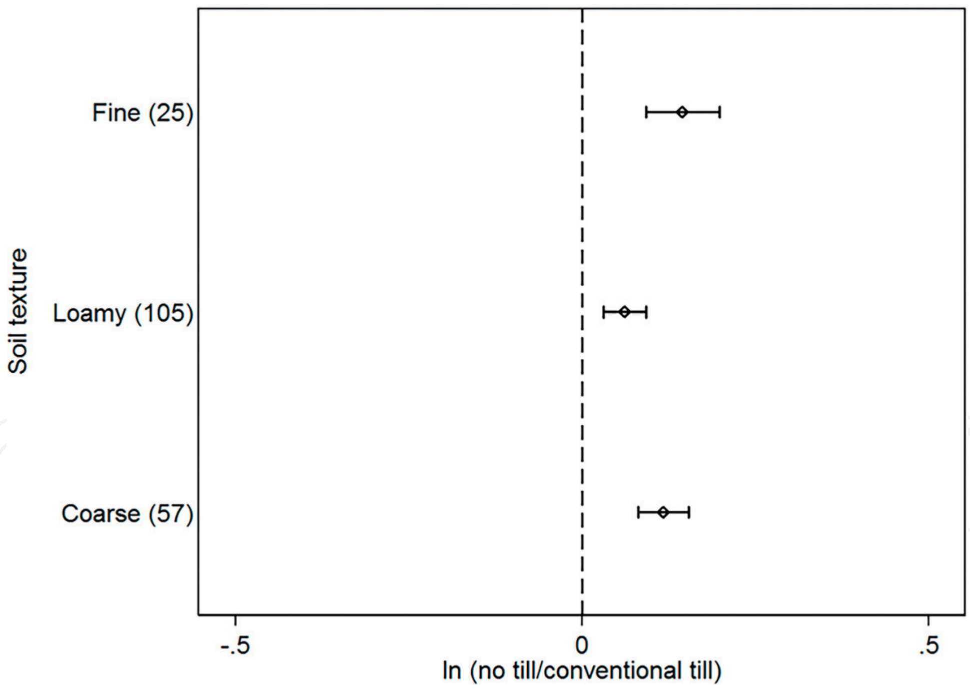

Figure 10. The effects of soil texture on paired log difference of soil organic carbon measurement between no till and conventional till (95% confidence intervals are shown and numbers of observations are included in parentheses).

Management practice from conventional tillage to conservation tillage is found to increase SOC levels; however, this is not always effective, especially in fine-textured and poorly drained soils and cold weather conditions [53–56]. Moreover, it is possible that no till or conservation till could

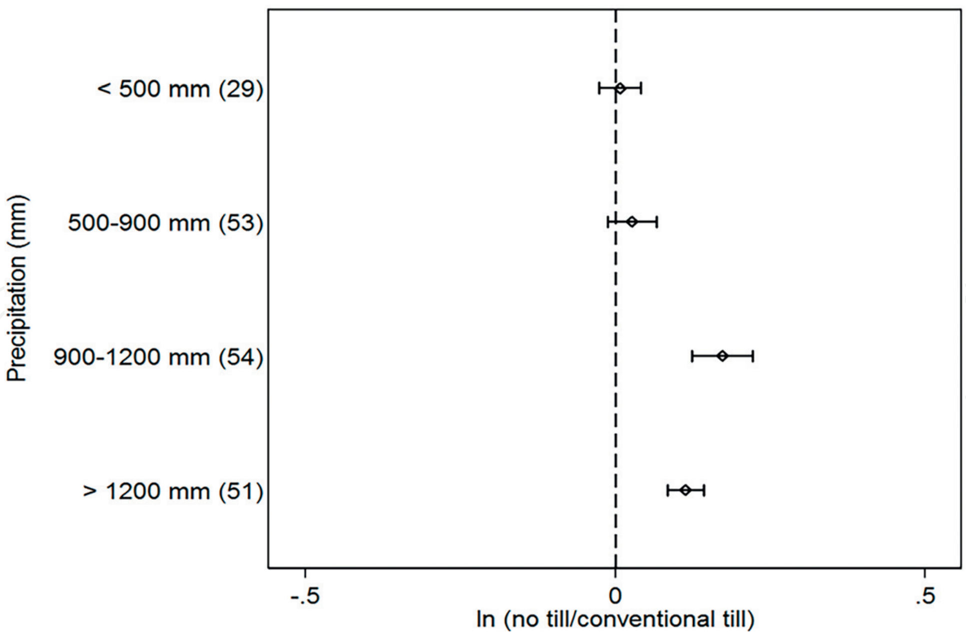

Figure 11. The effects of mean annual precipitation on paired log difference of soil organic carbon measurement between no till and conventional till (95% confidence intervals are shown and numbers of observations are included in parentheses).

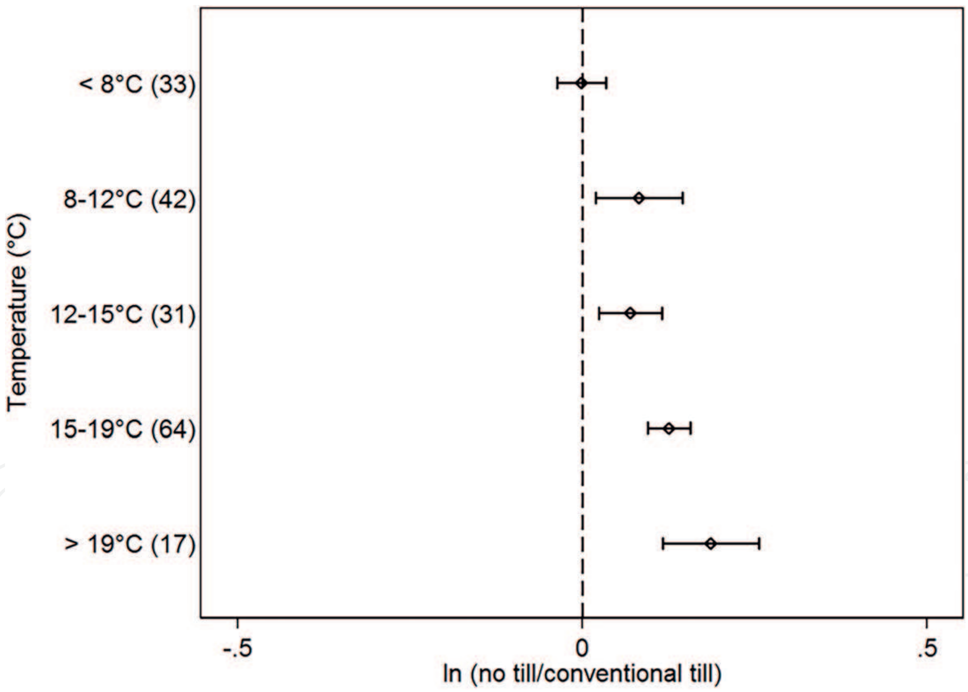

Figure 12. The effects of mean annual temperature on paired log difference of soil organic carbon measurement between no till and conventional till (95% confidence intervals are shown and numbers of observations are included in parentheses).

contribute to N_2O emissions, another GHG with even stronger climate warming potential [57–59]. The estimated N_2O emissions as a result of no till management are varied and inconsistent: some reported positive impacts, whereas some reported negative or no measurable impacts on

N_2O emissions [60]. The N_2O emissions may counterbalance all or some of the increased SOC content in terms of GHG mitigation potential in agriculture [61]. Therefore, to assess the capability of conservation tillage systems in mitigating global climate change, a systematic evaluation of all GHG emissions should be considered. Nonetheless, conservation tillage systems are a viable option that can sequester CO_2 from the atmosphere.

4. Conclusion

This review quantitatively evaluated the impacts of nitrogen fertilization management and conservation tillage systems on SOC stocks in the agricultural soils of the United States. The results presented here showed that N fertilizer additions had significant positive impact on SOC content, but the magnitude of this effect varied. In fact, the effect of N fertilization treatment on SOC stocks was moderated by cropping rotation system. As the cropping intensity increased, measured SOC content under fertilized treatment also increased. Soil texture and climate conditions, including mean annual temperature and mean annual precipitation, did not have significant impacts on differences of measured SOC stocks between fertilized and control treatments.

Significant differences in SOC stocks were found between no till and conventional till, as well as between no till and reduced till. However, SOC stocks between no till and reduced till were not significantly different. Differences of SOC content due to management changes from conventional tillage to no till system were significantly larger when treatment duration was longer. This study also showed a delayed response of SOC level to no till management with increases in measured SOC occurring beyond 5 years. Crop rotation system, soil texture, mean annual temperature, and mean annual precipitation did not have significant effects on SOC stocks. To summarize, paired log differences of measured SOC content from conventional tillage to conservation tillage were only significantly dependent on time since management.

To help combat global climate change, it is of great importance to identify changes in land management practices that can promote carbon sequestration and mitigate the enhanced greenhouse gas effect. The study recorded the responses of SOC stocks to changes in management practices and confirmed that adoption of N fertilizer additions and conservation tillage systems can contribute to increased SOC stocks in the agricultural soils of the United States. However, the evaluation of net carbon dioxide mitigation potential of these two recommended management practices should be carried out using a full carbon and greenhouse gas accounting method, which comprehensively considers both carbon input and carbon output to the agricultural systems. To conclude, agricultural soils can act as an important carbon sink to offset atmospheric CO_2 emissions when management practices are designed appropriately, as well as with proper incentives and technological advancements. Confidence intervals for estimates of carbon sequestration rates in this study can be incorporated in policy and carbon cycle modeling analysis to provide more accurate estimates of C sequestration potential at regional and global scales.

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