Effects of conservation tillage on crop yield and soil organic carbon in Northeast China

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Abstract

Northeast China(NEC) is the main grain-producing area in China, but soil degradation is severe due to the long-term use of conventional tillage(CT). It is necessary to restore soil fertility, maintain crop yield, and enhance sustainability using conservation tillage in NEC. However, the integrated effects of conservation tillage on crop yield and SOC under different conditions in NEC are still unclear. Using 70 peer-reviewed papers, we assessed the crop yield and SOC sequestration effect, and their relationship under no-till(NT), ridge tillage(RT), and subsoiling tillage(ST) in NEC. The results indicated that in areas with a mean annual temperature (MAT) < 3, yield under NT was significantly lower than CT by 3.7% whereas RT and ST were higher than CT by 0.8% and 13.1% ($P<0.05$). RT generally had a similar effect on yield as NT, but RT did not have a negative impact on yield in colder regions, indicating that this may be a more suitable conservation tillage practice in these areas. ST may be used in rotation with other tillage measures to maintain crop yield if necessary. NT could increase SOC concentration by 24.1%, 43.9%, and 17.4% under high MAT (>6), low mean annual precipitation (MAP) (<500mm), and continuous cropping, respectively. The mean SOC sequestration rate under NT, RT, and ST was 0.953, 0.099, and 0.101 Mg C ha-1 yr-1, respectively. Overall, the implementation of different conservation tillage measures in NEC can enhance crop yield as well as carbon sequestration, indicating its potential to be popularized in NEC.

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Abstract

Northeast China(NEC) is the main grain-producing area in China, but soil degradation is severe due to the long-term use of conventional tillage(CT). It is necessary to restore soil fertility, maintain crop yield, and enhance sustainability using conservation tillage in NEC. However, the integrated effects of conservation tillage on crop yield and SOC under different conditions in NEC are still unclear. Using 70 peer-reviewed papers, we assessed the crop yield and SOC sequestration effect, and their relationship under no-till(NT), ridge tillage(RT), and subsoiling tillage(ST) in NEC. The results indicated that in areas with a mean annual temperature (MAT) < 3, yield under NT was significantly lower than CT by 3.7% whereas RT and ST were higher than CT by 0.8% and 13.1% ($P<0.05$). RT generally had a similar effect on yield as NT, but RT did not have a negative impact on yield in colder regions, indicating that this may be a more suitable conservation tillage practice in these areas. ST may be used in rotation with other tillage measures to maintain crop yield if necessary. NT could increase SOC concentration by 24.1%, 43.9%, and 17.4% under high MAT (>6), low mean annual precipitation (MAP) (<500mm), and continuous cropping, respectively. The mean SOC sequestration rate under NT, RT, and ST was 0.953, 0.099, and 0.101 Mg C ha^{-1} yr^{-1}, respectively. Overall, the implementation of different conservation tillage measures in NEC can enhance crop yield as well as carbon sequestration, indicating its potential to be popularized in NEC.

Keywords

Conservation Tillage; SOC Sequestration; Crop Yield; Northeast China; Soil Degradation; Synthesis Analysis

Introduction

Soil has the largest organic carbon pool of the terrestrial ecosystems, containing three to four times that present in the atmosphere (Lal, 2008; Sanderman, Hengl, & Fiske, 2017). However, the conversion of natural lands to cropping causes depletion and degradation of soil organic carbon (SOC) (Don, Schumacher, & Freibauer, 2011; Guo & Gifford, 2002; X. R. Wei, Shao, Gale, & Li, 2014). The destruction of soil aggregate during tillage, which exposes previously protected SOC to decomposition, combined with decreased inputs of organic matter under cropping are the main reasons for the SOC loss after conversion to cropland. This depletion and degradation of SOC can affect crop yield due to its role in sustaining soil quality (Page, Dang, & Dalal, 2020; Reeves, 1997). Therefore, agricultural practices that sequester SOC are needed to restore soil fertility and advance food security.

Northeast China (NEC) (Fig. 1) , including Heilongjiang, Jilin, Liaoning Province, and the northeast part of Inner Mongolia Autonomous Region, is responsible for a large proportion of China's grain production, with three of its provinces (Heilongjiang, Jilin, and Liaoning Province) accounting for 30.9% and 44.4% of China's total production of maize (*Zea mays* L.) and soybean (*Glycine max* Merril.), respectively (NBSC, 2020). The black soil (Mollisols) region (43 - 50°N, 124 - 127°E) in NEC covers an area of 5.96 million hectares (Xiong & Li, 1987) and is extensively used for grain production, playing an important role in national food security (T. C. Wang, Wei, Wang, Ma, & Ma, 2011).

However, because of long-term cultivation and erosion caused by poor agricultural practices, soil degradation is severe in NEC, and it seriously threatens the sustainable development of agriculture (Jia, Ma, Li, & Chen, 2010). Conventional tillage (CT) in NEC, which is characterized by crop residue removal after harvest and deep moldboard or rotary plowing in the fall, has led to large losses of SOC (Somasundaram et al., 2018; Xie et al., 2014; Zhao et al., 2015). It has been reported that the annual loss of SOC stocks in NEC could reach 2.05 Mg ha^{-1} (Qiu, Wang, Tang, Li, & Li, 2004).

To alleviate this soil degradation, conservation tillage practices, e.g., no-tillage (NT), ridge tillage (RT) and subsoiling tillage (ST) with minimal soil disturbance, have been considered as an alternative to CT and have been greatly popularized in NEC. After conversion to conservation tillage, SOC accumulation and soil quality in the region are often improved in upper soil depths due to reduced disruption of soil aggregates (Sarker et al., 2018; Song et al., 2016; X. Wang et al., 2019). The restoration of SOC can not only reverse the degradation trends, but also enhance ecosystem services (Banwart et al., 2015; Lal, 2020).

Moreover, subsoiling can effectively reduce soil compaction and increase root distribution in deeper soil, which eventually increases soil water storage and has a positive effect on grain yield in China (Qiang et al., 2019; X. F. Sun et al., 2017) and around the world (Getahun et al., 2018; Yalcin & Cakir, 2006).

While the effectiveness of conservation tillage in reducing soil erosion and enhancing soil quality are generally expected to increase crop yield (Lal, 2004; Lal, Reicosky, & Hanson, 2007; Triplett & Dick, 2008), previous research has indicated that its impact can vary depending on climate. Positive effects are generally observed on crop yield in warm and dry climate zones (Cullum, 2012; Govaerts, Sayre, & Deckers, 2005; Kan, Liu, He, et al., 2020; Pittelkow, Liang, et al., 2015; Verhulst et al., 2011; Zhao et al., 2017), while in cool-humid areas, conservation tillage can have a negative impact (Anken et al., 2004; Arvidsson, Etana, & Rydberg, 2014). Some other studies have also reported no effect of SOM on crop yield (Hijbeek et al., 2017; Oelofse et al., 2015; W. L. Wei et al., 2016).

In the past five years, conservation tillage has been recommended by government in NEC, and the area using conservation tillage grew to 2.67 million hectares in 2020 with the aim of 9.33 million hectares by 2025 (The Ministry of Agriculture and Rural Affairs of China, 2020). However, the application of conservation tillage is region-specific, and the effect of application is closely related to environmental and socioeconomic conditions. Compared to other areas where conservation tillage has been widely adopted, such as the US, the application of conservation tillage in NEC still needs improving and perfecting. At present, conservation tillage machines, especially no-tillage planters, still have some problems, such as poor adaptability, low operating efficiency, and high price (Y. F. Liu, Lin, & Li, 2017; X. R. Wei et al., 2014). In addition, the mode of conservation tillage suitable for development in different regions also needs to be better determined. The mean annual temperature in NEC varies from < 0 to > 10 , and annual precipitation ranges from 400 - 800 mm. Under global warming, the climate in NEC will also change, leading to uncertainty for the effects of conservation tillage, yet little is known about this. Therefore, it is important to identify different tillage effects on yield and SOC under different conditions.

The objectives of this study were to: (i) assess the effects of different tillage practice on crop yield and SOC sequestration in NEC; (ii) estimate the relation between SOC and crop yield in NEC; and (iii) provide some recommendation for the application of different conservation tillage practices in NEC. We hypothesize that there is no single tillage method suitable for the whole area of NEC, and different conservation tillage measures will have their own advantages under different planting and meteorological conditions in crop yield and carbon sequestration.

2. Materials and methods

2.1. Data collection

Data were collected from peer-reviewed papers published in both the Chinese and English literature before 2020. Papers were identified using the Web of Science (Clarivate Analytics) and the China Knowledge Resource Integrated Database (*www.cnki.net*). Search terms included "conservation tillage", "no-till", "ridge tillage", "subsoiling" with selected papers restricted to those conducted in Northeast China. The following criteria were considered when selecting the properly paired experiments to avoid any publication bias: (1) except tillage measures (conservation tillage and conventional tillage), other experimental conditions must be the same; (2) the experiment duration under conservation tillage and conventional tillage must be the same; (3) data on crop yield and (or) SOC concentration/storage under conservation tillage and conventional tillage must be given; (4) the experiment must have been conducted under field conditions. Based on the above criteria, a total of 176 pairs of experimental data were available for analysis, among which 148 were crop yield data, and 65 were SOC data (including 37 pairs of data for both crop yield and SOC). Data were collected from about 70 articles, including 25 experiment sites located in Northeast China excluding the northeast part of Inner Mongolia Autonomous Region (Fig.1). The details of selected 25 sites are listed in Table S1. The experimental sites were mainly distributed in the main grain-producing areas such as Sanjiang Plain and Songnen Plain.

Fig. 1

Three tillage practices were selected for analysis, no-tillage (NT), ridge tillage (RT, including RT with minimal soil disturbance), and subsoiling tillage (ST, including in rotation tillage with NT). Under NT, the soil was not disturbed except for planting using a no-till planter. RT was characterized by ridge building with a cultivator and no-till planter was also used for seeding. ST required deep loosing operation to ˜30 cm and it was often conducted as a one off operation in NT and RT system. Conventional tillage (CT) was chosen as a control for calculating the effects of the three practices on crop yield and/or SOC concentration. Other site characteristics such as mean annual temperature (MAT), mean annual precipitation (MAP), crop planting pattern, experiment duration, and other soil physical and chemical indicators were also collected.

Mean annual temperature (MAT) of these studies ranged from 0.5 to 10.4 , mean annual precipitation (MAP) from 407.7 to 714.0 mm, and experimental duration from 1 to 32 yrs. According to the quantity and distribution of data, studies were divided into categorical groupings, as listed in Table 1.

Table 1

2.2. Data analysis

To evaluate the effects of conservation tillage practices on crop yield, SOC concentration and other soil physical and chemical characteristics, we used the natural log of the response ratio (lnR) to calculate the effect size. The natural log of the response ratio is widely-used in meta-analysis of ecology studies (Hedges, Gurevitch, & Curtis, 1999), and calculated using Equation (1)

$\ln R = ln\frac{x_1}{x_2}$ (1)

Where, x_1 and x_2 stand for crop yield / SOC concentration under conservation tillage and conventional tillage, respectively. The ln R is the effect value of conservation tillage. The effects of other soil physical and chemical indicators were also calculated using Equation (1).

SOC concentration at the depth of 0-5 and 0-20 cm were collected. Where studies reported soil organic matter (SOM), Equation (2) was used to convert SOM into SOC concentration.

$SOC = 0.58 \times SOM \times 0.1$ (2)

Where, SOC is soil organic carbon concentration, g kg^{-1}; SOM is the concentration of soil organic matter, %; 0.58 is the conversion factor (Nelson & Sommers, 1982).

Soil organic carbon storage (SCS) in the 0-20 cm soil depth was also collected because this is an important index to evaluate soil fertility and a more robust indicator of SOC sequestration than concentration data as it takes into account differences in bulk density among management practices. For most studies, only SOC concentration and soil bulk density were provided, and SCS was calculated using the equivalent mass method (Ellert & Bettany, 1995) with Equation (3):

$SCS = [M \times SOC + (M_{\max} - M) \times \mathrm{SOC}_{\mathrm{extra}}] \times 0.001$(3)

$M = BD \times 0.2 \times 10000$ (4)

where, SCS is soil organic carbon stocks, Mg/ha; M is the determined equivalent soil mass of 0-20 cm and M_{max} means the maximum soil mass at depth of 0-20 cm under different tillage practices (NT, RT, ST, and CT); SOC is soil organic carbon concentration, g kg^{-1}; $SOC_{extra}$is the added SOC concentration, g kg^{-1}; 0.001 is the coefficient of mass unit kg converted to Mg. For the calculation of soil mass, Equation (4) was used, where BD is the soil bulk density, Mg m^{-3}; 0.2 is the thickness of the soil layer, m; 10000 is the coefficient of area unit m^2 converted to ha.

Based on the differences in SCS between conservation tillage and conventional tillage, the annual SOC sequestration rate (SOC_{SR}, Mg $ha^{-1}yr^{-1}$) of different conservation tillage measures in Northeast China were also calculated, using Equation (5):

$\mathrm{SOC}_{\mathrm{SR}} = \frac{\mathrm{SCS}_t - \mathrm{SCS}_c}{d}$(5)

where, SCS_t and SCS_c represent SOC stocks (0-20 cm) under conservation tillage and conventional tillage, respectively (Mg ha^{-1}); d is the duration of experiments (yr).

2.3. Statistical analysis

Analysis of variance (ANOVA) was conducted to test the treatment effects on SOC and yield with the least significant difference (LSD) at $P < 0.05$ level. Pearson correlation analysis was conducted between SOC/crop yield and site conditions along with other soil physical and chemical indicators to determine their relationships. For all analyses, we used SPSS software 25.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Effects of Conservation Tillage Practices on Crop Yields

Fig. 2

Overall, based on 148 observations, the mean effect value of yield under conservation tillage is 0.0443, with a 95% confidence interval (CI) from 0.0249 to 0.0636, indicating that crop yield can be increased by an average of 4.53% (2.52%-6.57%, $P < 0.001$) under different conservation tillage measures in NEC (Fig. 2). However, the large range in yield effect (-0.4073 to 0.4715), indicates that yield has responded differently in different studies, and that to apply conservation tillage practices appropriately it will be necessary to understand those conditions that effect the magnitude and direction of yield change.

Fig. 3

In cold areas (MAT < 3), yield under NT was significantly lower than CT as well as ST ($P < 0.05$), with yield reductions of 3.7% compared to CT (Fig. 3a). Under warmer temperature regimes (MAT > 6), crop yield under NT was increased by 13.1%, which was significantly higher than NT in colder areas (MAT < 6) ($P < 0.05$). RT showed a similar trend to NT as MAT increased, but yield effect under RT was above 0 all the time, which indicated a trend for better yields under RT compared to NT under cooler temperatures (Fig. 3a).

NT had a negative effect on yield ($P < 0.05$) when MAP was 500 - 600 mm, with crop yield reduced by 1.4% compared to CT (Fig. 3b). However, when MAP was either < 500 mm or > 600mm, NT had a positive impact on yield ($P < 0.05$). Under a rotational cropping pattern, crop yield decreased by 0.5% under NT and increased 1.9% under RT compared to CT, but both of them were significantly lower than that under ST ($P < 0.05$), which increased 16.7% compared to CT (Fig. 3c). Under a continuous cropping pattern, all the conservation tillage measures improved yield relative to CT, but the difference among them was not significant (Fig. 3c). As the period of experiment duration increased, the yield effect with conservation practices also tended to increase, although this was only significant for ST. When duration > 8 yrs, the difference between NT and other tillage practices was not significant (Fig. 3d).

3.2. Effects of Conservation Tillage Practices on SOC Concentration

Fig. 4

Based on 65 pairs of SOC data, the mean value of SOC effect is 0.078 (Fig. 4), with a 95% CI of 0.0422 - 0.1138, indicating that conservation tillage measures could significantly improve SOC concentration at 0-20cm by an average of 8.1% (4.3% - 12.1%, $P < 0.001$) compared to CT.

Fig. 5

NT generally had a positive effect on SOC concentration regardless of experimental conditions, but especially under high MAT (> 6), low MAP (< 500 mm), and continuous cropping patterns, which significantly increased SOC concentration compared to CT by 24.1%, 43.9%, and 17.4%, respectively (Fig. 5). Similar to NT, RT and ST also had a generally positive effect on SOC concentration, but the degree of ascension was not often as great as NT.

With the increase of MAT, the effects of SOC under NT and ST increased significantly ($P < 0.05$). Under high MAT (> 6) ST and NT showed a large increase in SOC concentration compared to CT (22.3% and 24.1%, respectively), but when MAT was lower than 6 , the effect size decreased and ST even had a negative effect (-1.2%) at $0-3$ (Fig. 5a). When MAP < 500mm, NT had a significant higher ($P < 0.05$) effect value than in more humid areas (MAP > 500 mm) (Fig. 5b). Under continuous cropping, NT had a significantly higher value ($P < 0.05$) than under a rotational pattern, while the improvement in SOC under RT was not affected by the type of cropping pattern employed (Fig. 5c). Time had no significant impact on SOC for NT or ST treatments, although SOC concentration under RT increased in longer duration experiments, increasing significantly ($P < 0.05$) from 0.1% to 4.1% greater than CT (Fig. 5d).

Fig. 6

The range of SOC sequestration rates varied greatly from -1.256 (under ST) to 5.320 (under NT) Mg C $ha^{-1}yr^{-1}$ (Fig. 6). The mean value of SOC sequestration rate under NT, RT, and ST was 0.953, 0.099, and 0.101 Mg C ha^{-1} yr^{-1}, respectively. The SOC sequestration rate under NT was significantly higher than that under RT ($P < 0.05$), although there was non-significant difference between NT and ST or ST and RT. Based on all the data under conservation tillage measures, the mean value of SOC sequestration rates is 0.658 Mg C ha^{-1} yr^{-1}, indicating that conservation tillage can enhance SOC sequestration in NEC.

3.3. Relationships between Yield and SOC

Fig. 7

There was a significant quadratic relationship between SOC concentration and maize yield ($R^2 = 0.549$, $P < 0.001$) (Fig. 7a) and between SCS and maize yield ($R^2 = 0.513$, $P = 0.005$) (Fig. 7b) under NT. A quadratic relationship was also observed between RT and SCS, however, this was not significant ($R^2 = 0.531$, $P = 0.15$). For most experiments conducted in NEC where SOC concentration and stock were under 20 g kg^{-1} and 50 Mg ha^{-1}, respectively, maize yield showed a positive correlation with SOC concentration and SOC stock, which stressed the importance of SOC concentration and restoration in maintaining the yield of the crop in NEC. Because of the lack of data, yield of soybean and other crops are not shown.

3.4. Factors affecting Yield and SOC

There were no significant relationships between yield effect and other site characteristics for any of the tillage practices (Table 2). SOC (0-20cm) was significantly correlated with SOC (0-5 cm) and SCS under NT ($R^2 = 0.788$, $R^2 = 0.998$, $P < 0.01$) and RT ($R^2 = 0.965$, $R^2 = 0.900$, $P < 0.01$), and ST showed a significant positive correlation ($P < 0.01$) with SCS. Significant correlations ($P < 0.01$) were also observed between SOC effect and TN ($R^2 = 0.882$), C/N ($R^2 = 0.843$), and BD ($R^2 = 0.844$) under NT. Under NT and ST, pH effects were negatively but not significantly correlated with the SOC effect. NT and RT all showed a non-significant negative correlation between water content and SOC, while ST showed a positive one.

Table 2

Fig. 8

There was a significant quadratic relationship between MAT and maize yield under NT ($R^2 = 0.408$, $P < 0.001$, Fig. 8a) and RT ($R^2 = 0.576$, $P < 0.001$, Fig. 8a), with yield peaking at ˜6.5 degC in both treatments before declining. In contrast, a negative linear relationship was observed for ST treatments ($R^2 = 0.335$, $P = 0.001$, Fig. 8a). There was also a significant positive linear relationship between maize yield and MAP under NT ($R^2 = 0.089$, $P=0.035$), and a quadratic relationship under ST ($R^2=0.51$, $P<0.001$), although no significant relationship between maize yield and MAP was observed for RT (Fig. 8b). However, under high MAP condition (˜700 mm) little difference was observed among the three conservation tillage measures (Fig. 8b).

No significant relationships were observed between soybean yield and MAT or MAP. However, there was a trend for a negative linear relationship between yield and MAT under NT and RT, and a positive linear relationship under ST (Fig. 8c). There was also a trend towards a positive linear relationship were between soybean yield and MAP for all tillage treatments (Fig. 8d).

The SOC concentration at 0-20 cm under NT (R^2 = 0.758, P < 0.001), RT (R^2 = 0.932, P < 0.001) and ST (R^2 = 0.655, P = 0.027) decreased with increasing MAT (Fig. 9a). But the change in SOC as MAT increased above 7degC was minimal. A quadratic relationship was observed between SOC and MAP for NT (R^2 = 0.293, P = 0.003) and ST (R^2 = 0.886, P = 0.013) treatments, with SOC peaking at ˜ 600 and 500 mm in NT and ST treatments, respectively, before declining (Fig. 9b). A significant positive linear relationship was observed between SOC and MAP for RT treatments (R^2 = 0.762, P < 0.001), although only limited datapoints (MAP range from ˜500 to ˜550 mm) were available, and further data is needed to confirm this relationship.

Fig. 9

4. Discussion

4.1. Factors affecting crop yield

Our data indicated that at low MAT (0-3 degC), crop yield under NT was lower compared to CT (Fig. 3a). In NEC, many studies have reported similar findings (Y. Chen et al., 2011; S. Liu, Zhang, Kravchenko, & Iqbal, 2015), and similar results were also reported in other cooler regions worldwide (Malhi, Mumey, Osullivan, & Harker, 1988; T. D. West, Griffith, Steinhardt, Kladivko, & Parsons, 1996). This yield decline is often attributed to the lower soil temperatures under NT compared with CT in spring (Chassot, Stamp, & Richner, 2001; Drury et al., 1999; S. Liu et al., 2015; Sarkar & Singh, 2007), due to the lack of soil disturbance, which can lead to delays in maize emergence and a shorter growing period, thus causing a decline in yield (Soane et al., 2012). The straw mulching employed in NT is also a possible reason for the decrease in yield (Y. Chen et al., 2011; S. Liu, Zhang, Yang, & Drury, 2013), as this contributes to lower soil temperature and higher soil water concentration (Linden, Clapp, & Dowdy, 2000; X. J. Lu, Li, Sun, & Bu, 2015). However, in our research, as MAT increased, maize yield did not rise linearly (Fig. 8a), possibly because in higher temperature regions (e.g., southern part of NEC) lower concentrations of SOC were also observed, particularly above 7 (Fig. 9a). Therefore, RT may be a better conservation tillage practice in the colder areas of NEC than NT given its reduced impact on yield (Fig. 3a), likely due to the greater soil temperature under RT, which is very important in NEC in spring (He, Li, Kuhn, Wang, & Zhang, 2010). However, RT could still prevent the yield loss that occurs under CT when strong wind and heavy rain leads to lower crop lodging (Liang et al., 2017), which is particularly important during extreme weather events, such as typhoons.

The MAP also affected crop yield under conservation tillage. We observed that when MAP was either < 500 or > 600 mm, NT had a positive impact on yield, while when MAP was 500 - 600mm NT had a negative effect (Fig. 3b). Page et al. (2019) reported that the increased water infiltration and stocks common under NT can increase the soil water available for crop growth, providing a yield advantage compared to CT in drier regions, which could explain the improved yield observed in lower rainfall regions in the current study. The area of the NEC that experiences a MAP of 500 – 600 mm, mainly occurs in Heilongjiang Province, where MAT is also lower. Based on a global meta-analysis, W. J. Sun et al. (2020) reported that temperature might have a greater influence on yield in cold, arid areas, and this may explain the yield decrease observed in the current study.

Crop rotation is now recommended by government in NEC, however, our results found that NT with a rotational crop pattern decreased crop yield compared to CT (Fig. 3c). The reason for this might be that the main areas where crop rotation is applied are relatively cold and cool, and cooler temperature decreases crop yield under NT. However, there is abundant evidence for studies worldwide that rotation plays an important role in restoring soil fertility (Dumanski et al., 1998; Havlin, Kissel, Maddux, Claassen, & Long, 1990; Lal, Follett, Kimble, & Cole, 1999), so a rotational cropping pattern with RT or ST are likely to be most appropriate for cooler regions in NEC.

The adopted duration of conservation tillage also had an impact on the crop yield effect for ST. When ST had been in place for < 8 yrs, the yield improvements were smaller than when tillage practices had been in place for > 8 yrs (Fig. 3d). For the NT and RT treatments, there was a also trend towards increasing yield when practices had been in place for >8 yrs, although this was not significant. Other studies have reported that crop yield can increase when conservation tillage has been in place for both short (4 yrs) and long (12 yrs) periods of time (You et al., 2017; Zhang et al., 2015), however, a recent meta-analysis found that negative crop yield was commonly observed up until ˜5 yrs (Pittelkow, Linquist, et al., 2015). The rise of yield effect in long experiments is possibly caused by the decrease of yield under CT as the soil degrades, as well as the improvements in soil structure under conservation tillage measures.

Similar to our findings, many studies also reported that ST has a significant positive effect on crop yield in northeastern and other parts of China (Feng et al., 2018; X. F. Sun et al., 2017). By loosening the soil, ST can increase rooting depth (Rajkannan & Selvi, 2002), improve infiltration and water storage (Peeyush, Tripathi, Surendra, & Ravindra, 2004; Rajkannan & Selvi, 2002), and finally increase crop yield. Therefore, tillage mode like ST rotated with NT, e.g., ST-NT-NT in 3 yrs, which has already been popularized and applied in Heilongjiang Province (Gong, Qian, & Yu, 2009), could be considered for the whole NEC area. However, the high cost of undertaking ST is a significant barrier to the large-scale promotion of this practice.

4.2. Factors affecting SOC concentration

As the core practice of conservation tillage, NT has been demonstrated to improve SOC sequestration by reducing soil disturbance and enhancing physical protection of SOC within soil aggregates (Six, Elliott, & Paustian, 2000; Six et al., 2002). However, the ability of conservation tillage measures to sequester SOC is known to differ under different climatic conditions (Zhao et al., 2015). Our result showed that, as MAT rose, the SOC effect increased significantly under NT and ST ($P < 0.05$) (Fig. 5a), although the SOC concentration still declined under both these tillage practices as MAT increased (Fig. 9a). This would indicate that there was a slower downward trend in SOC under NT and ST than CT as temperature increased. Temperature is an important factor responsible for SOC stability and higher temperatures increase SOC mineralization (Dong et al., 2019; Kan, Liu, Wu, et al., 2020). The greater protection of SOC afforded under NT and ST practices may have thus reduced the impact of temperature on mineralization rates relative to CT. Greater biomass production at high temperatures (as indicated by the increased yield effect at higher temperatures for NT (Fig. 3a) would also have contributed to greater SOC concentrations under NT.

The SOC concentration effect under NT in drier areas (MAP < 500 mm) was also significantly higher than that in more humid areas ($P < 0.05$) (Fig. 5b). Previous meta-analyses have observed decreased C sequestration following the implementation of NT in dry (< 1000 mm) compared to moist (> 1000 mm) rainfall regions (Ogle, Breidt, & Paustian, 2005). However, the current study analysed papers conducted over a much narrower rainfall range (408 - 714 mm). Within this rainfall range, areas with lower precipitation (< 500 mm) led to greater SOC gain following the introduction of NT. However, the reason for this is not fully understood.

NT used in combination with continuous cropping led to higher SOC concentrations than CT, but when used with a rotational pattern, the increase in SOC relative to CT was smaller, and it is significantly lower than that under continuous cropping pattern (Fig. 5c), which is consistent with the results found by T. O. West and Post (2002). Previous studies had found that SOC concentration or stocks could be increased only when NT or other tillage measures combined with crop residue retention (Dolan, Clapp, Allmaras, Baker, & Molina, 2006; Villamil & Nafziger, 2015). Some other studies also reported that the amounts of residue retention played an important role in SOC accumulation, with the more residue returned to soil, the greater the impact on SOC (Kubar et al., 2018; Plaza-Bonilla, Alvaro-Fuentes, & Cantero-Martinez, 2014). The common mode of rotational cropping in NEC is maize-soybean alternately planted every year, which produces less residue than continuous maize pattern, and may be responsible for the lower SOC increase under rotation (X. W. Chen et al., 2011).

Experimental duration of conservation tillage should have an impact on SOC stocks, although the results are sometimes contradictory especially when duration is below 10 yrs (Liang, Chen, Zhang, & Chen, 2014; VandenBygaart et al., 2011; VandenBygaart, Gregorich, & Angers, 2003). Our results show no significant increase in the SOC effect over time for NT or ST treatments, although there was a small but significant increase ($P < 0.05$) in the SOC effect in RT treatments for experiments conducted for > 8 yrs (Fig. 5d).

The SOC sequestration rate under NT at the depth of 0-20cm in NEC is 0.953 Mg C ha^{-1} yr^{-1}, which is much higher than China's national average in the same layer of 0.157-0.390 Mg C ha^{-1} yr^{-1}(F. Lu et al., 2009). NT also had a significantly greater rate of sequestration than RT, and was trending higher than ST. This indicates that NT is likely to be an effective management strategy to sequester SOC and restore soil fertility in NEC.

4.3. The effects of SOC on crop yield

SOC can positively affect crop growth due to its impact on soil properties and processes (D'Hose et al., 2014; Doran & Zeiss, 2000). Previous studies have reported that SOC has a positively linear relation with crop yield (Lal, 2006; S. K. Wang et al., 2016). Our study found that maize yield had a positive relation with SOC concentration and stocks under NT up until ~20 g kg^{-1} or 40 Mg ha^{-1}, but then decreased as SOC concentration continued to rise (Fig. 9). Some studies reported that there is a threshold where the continuous increase of SOC will not always contribute to growth of crop yield (Hijbeek et al., 2017), with 20 g kg^{-1} was the threshold suggested in the temperate climate zone (Greenland, 1975; Lal, 2020; Loveland & Webb, 2003; Oldfield, Bradford, & Wood, 2019). Our results also found the linear relation between SOC and maize yield up to SOC concentration of 20 g kg^{-1}, but when SOC concentration increased to 30 g kg^{-1}, maize yield dropped greatly under NT (Fig. 9a). The reason for this might be the colder temperatures experienced in regions with higher SOC, which could override any benefits of higher SOC concentration on crop yield.

4.4. Outlook of future research

As the Chinese government published the project of conservation tillage application in NEC this year, it can be predicted that there will be more research on conservation tillage in NEC in the future. Based on our research, we hope that upcoming research can focus on the following issues: (i) the need for more study on the impact of RT on yield and SOC sequestration, due to the large use of RT by farmers in NEC; (ii) there has been relatively little research conducted in the Inner Mongolia Autonomous region, and more research is required to better understand the operation of conservation tillage in this region; (iii) most research has been conducted in flat regions, and more research should be conducted on sloping and mountainous areas in order to better understand the role of conservation tillage in preventing soil erosion,; and (iv) greater quantitative evaluation should be conducted of the combined impact of conservation tillage on the yield, environment and social aspects of crop production.

5. Conclusions

The impacts of conservation tillage on crop yield and SOC concentration are affected by site environmental characteristics. In the cold area (MAT 0 - 3degC) of NEC, crop yield decreased under NT compared with CT, and in these environments, RT may be the better tillage practice. However, as temperature increases, crop yield increases compared to CT when using NT practices. ST was also observed to have a positive impact on yield when rotated with other conservation tillage measures, thus confirming that this practice can be safely implemented if it is necessary to loosen compacted layers. Conservation tillage measures had a significant impact on SOC sequestration rate and thus contributed to greater SOC concentrations, especially in a continuous cropping pattern under NT. Additionally, SOC effect under NT was significantly correlated with TN, C/N, and soil bulk density. Below a SOC concentration of 20 g kg^{-1}, maize yield was found to increase linearly as SOC increased under NT, and magnitude of the yield increases under ST tended to be larger the longer ST had been in operation.

Overall, our data suggest that the appropriate use of different conservation tillage measures in different area in NEC could result in the win-win situation of crop yield increase and carbon sequestration, and will help protect soils from degradation and stabilize crop yield in NEC.

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Tables

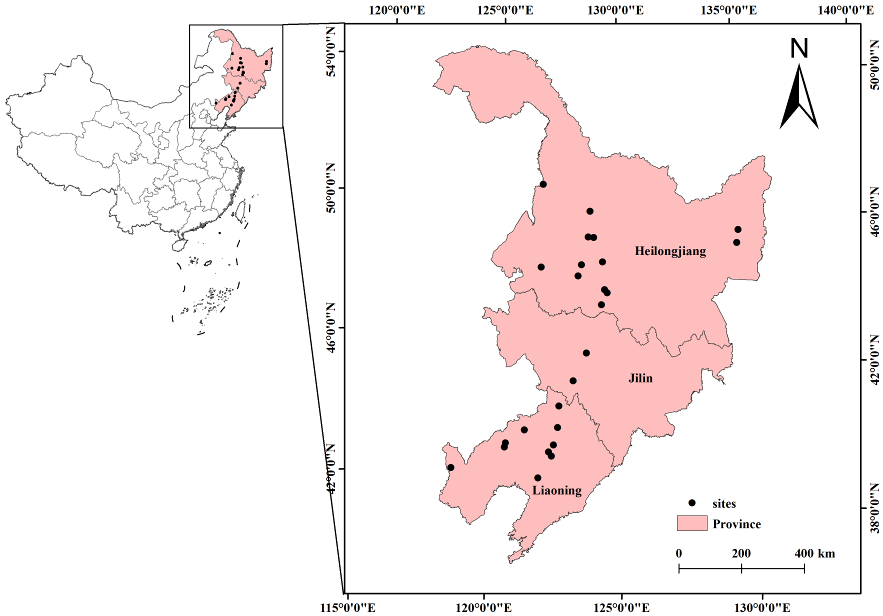
Table 1 Categorical groupings used for experimental site characteristics

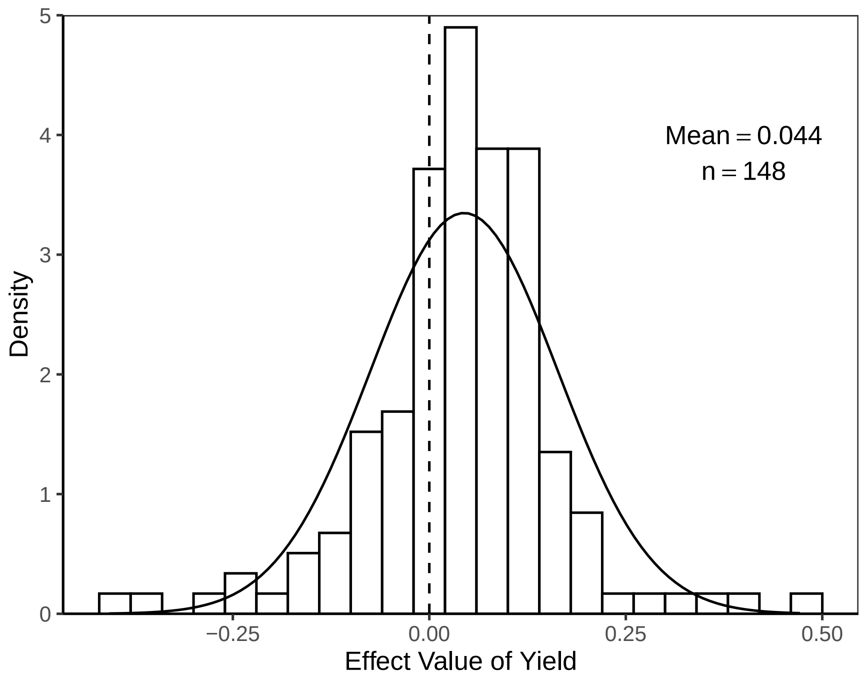
Categorical Variables	Groups	Groups	Groups	Groups
MAT()	0-3	3-6	>6	
MAP (mm)	<500	500-600	>600	
Cropping pattern	Continuous	Rotational		
Experiment duration (year)	1	2-4	5-8	>8
Dominant crops	Maize	Soybean	Rice	

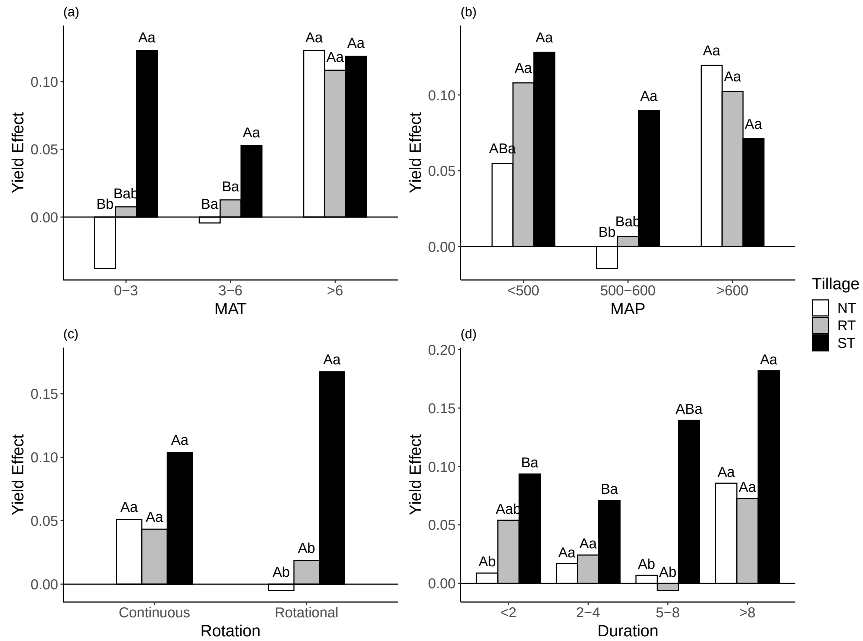
Table 2 Correlation analysis of site condition effects with yield and SOC effects

Indicators	Tillage	Yield Effect	n	SOC Effect (0-20 cm)	n
SOC(0-5cm)	NT	0.511	5	0.788**	12
	RT	0.363	3	0.965*	4
	ST	NA	NA	NA	NA
SOC(0-20cm)	NT	0.274	23		
	RT	-0.476	8		
	ST	0.698	5		
SCS	NT	0.039	18	0.998**	22
	RT	-0.622	8	0.900**	10
	ST	0.733	3	1.000**	3
MBC	NT	-0.659	5	-0.237	5
	RT	NA	NA	NA	NA
	ST	NA	NA	NA	NA
TN	NT	-0.124	16	0.882**	22
	RT	NA	NA	NA	NA
	ST	-0.419	5	-0.134	6
C/N	NT	0.036	7	0.843**	10
	RT	NA	NA	NA	NA
	ST	NA	NA	NA	NA
pH	NT	0.5	3	-0.615	8
	RT	NA	NA	NA	NA
	ST	-0.784	5	-0.706	6
BD	NT	-0.396	24	0.844**	22
	RT	0.278	13	-0.016	10
	ST	0.389	11	0.589	3
WC	NT	0.297	13	-0.083	14
	RT	-0.321	7	-0.915	4
	ST	-0.181	11	0.833	4

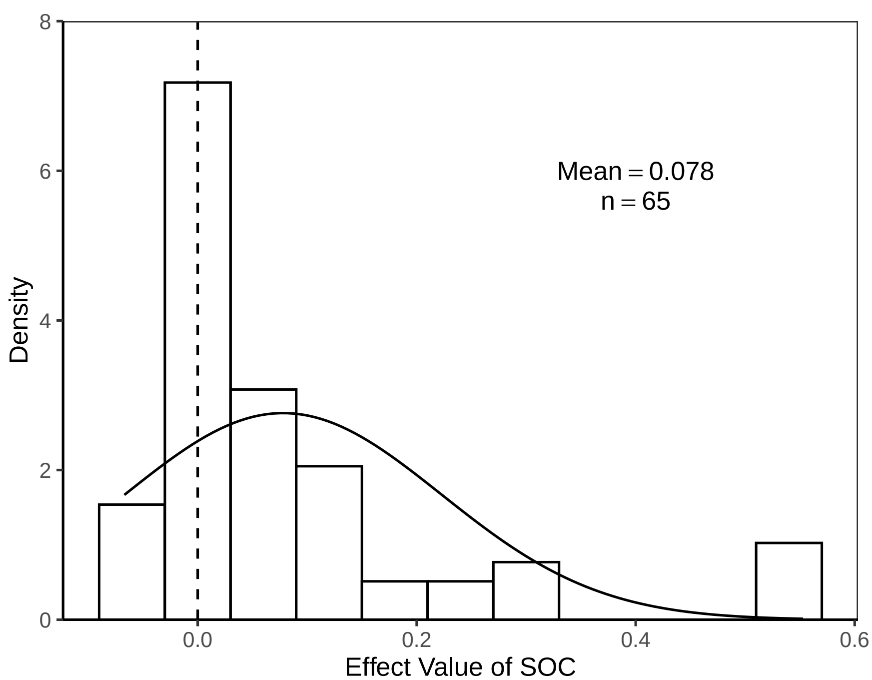
SCS, SOC stocks; MBC, microbial biomass carbon; TN, total nitrogen; BD, soil bulk density; WC, soil water concentration; NT, no-tillage; RT, ridge tillage; ST, subsoiling tillage. * means $P < 0.05$, ** means $P < 0.01$.


120°0'0"E
125°0'0"E
130°0'0"E
135°0'0"E
140°0'0"E
54°0'0"N
50°0'0"N
46°0'0"N
42°0'0"N
38°0'0"N
N
Heilongjiang
Jilin
Liaoning
sites
Province
0
200
400 km
115°0'0"E

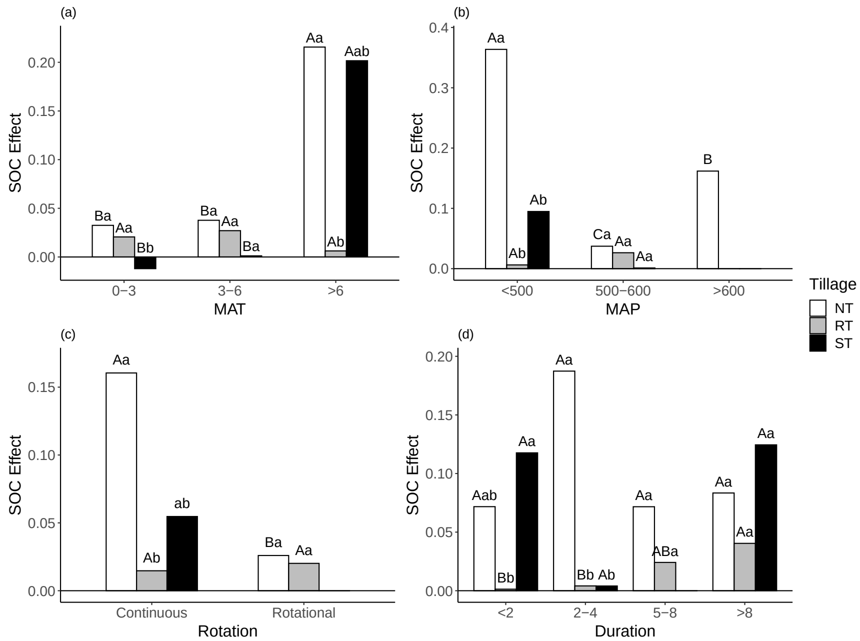

Mean = 0.044
n = 148
Density
Effect Value of Yield
−0.25
0.00
0.25
0.50
0
1
2
3
4
5

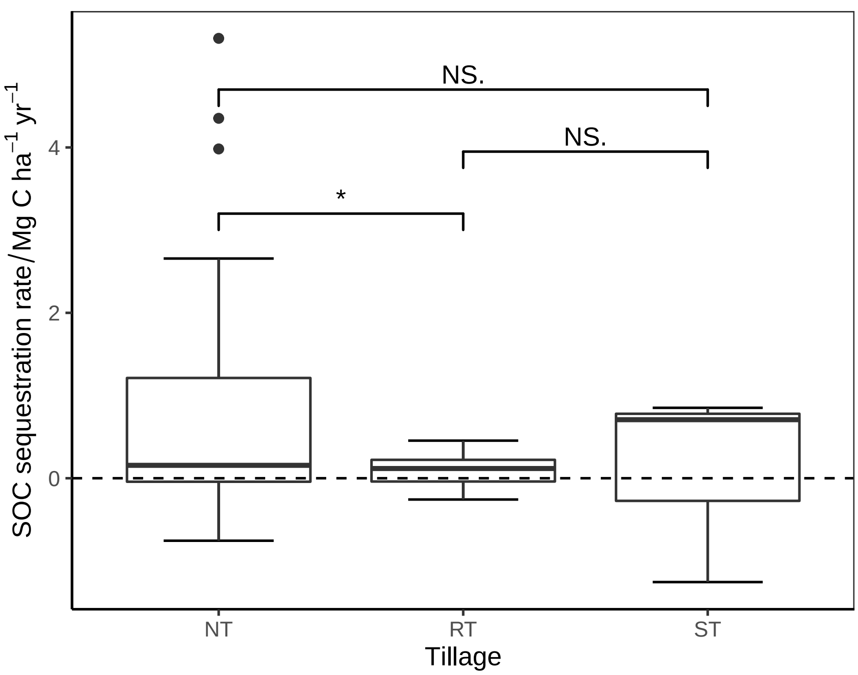


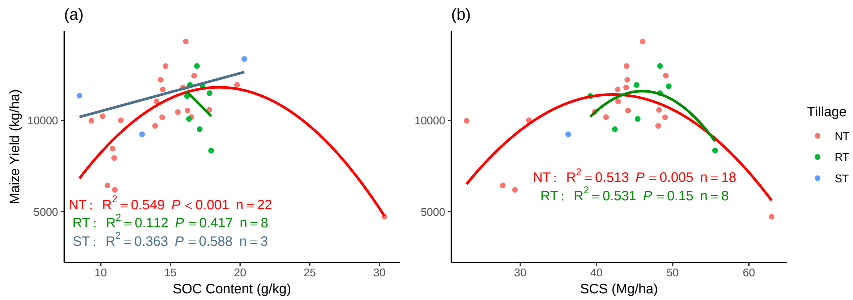
(a)
Yield Effect
MAT
0−3
3−6
>6
Bb
Bab
Aa
Ba
Ba
Aa
Aa
Aa
Aa
(b)
MAP
<500
500−600
>600
ABa
Aa
Aa
Bb
Bab
Aa
Aa
Aa
Aa
Tillage
NT
RT
ST
(c)
Yield Effect
Rotation
Continuous
Rotational
Aa
Aa
Aa
Ab
Ab
Aa
(d)
Yield Effect
Duration
<2
2−4
5−8
>8
Ab
Aab
Ba
Aa
Aa
Ba
Ab
Ab
ABa
Aa
Aa
Aa

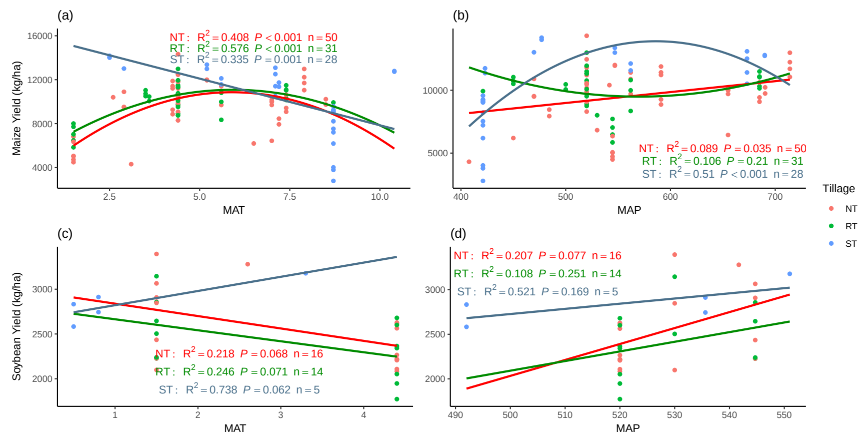


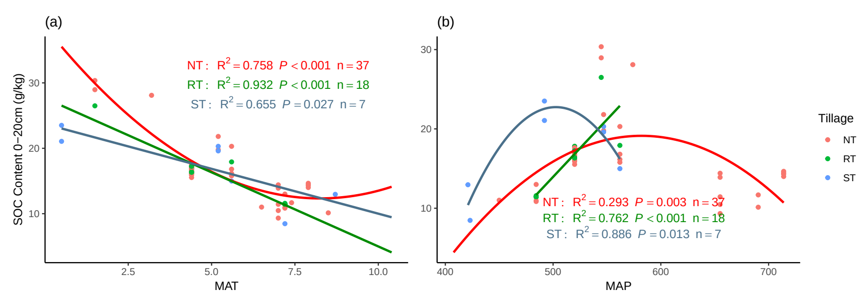
Density
Effect Value of SOC
Mean = 0.078
n = 65


(a)
(b)
(c)
(d)
SOC Effect
MAT
MAP
Rotation
Duration
0−3
3−6
>6
<500
500−600
>600
Continuous
Rotational
<2
2−4
5−8
>8
Tillage
NT
RT
ST
Ba
Aa
Bb
Ba
Aa
Ba
Aa
Ab
Aab
Aa
Ab
Ab
Ca
Aa
Aa
B
Aa
Ab
ab
Ba
Aa
Aab
Bb
Aa
Aa
Bb
Ab
Aa
ABa
Aa
Aa
Aa


SOC sequestration rate/Mg C ha^{-1} yr^{-1}
NS.
NS.
*
0
2
4
NT
RT
ST
Tillage


(a)
(b)
Maize Yield (kg/ha)
SOC Content (g/kg)
SCS (Mg/ha)
NT: $R^2 = 0.549$ $P < 0.001$ n = 22
RT: $R^2 = 0.112$ $P = 0.417$ n = 8
ST: $R^2 = 0.363$ $P = 0.588$ n = 3
NT: $R^2 = 0.513$ $P = 0.005$ n = 18
RT: $R^2 = 0.531$ $P = 0.15$ n = 8
Tillage
NT
RT
ST


(a)
(b)
(c)
(d)
Maize Yield (kg/ha)
Soybean Yield (kg/ha)
MAT
MAP
NT: $R^2 = 0.408$ $P < 0.001$ n = 50
RT: $R^2 = 0.576$ $P < 0.001$ n = 31
ST: $R^2 = 0.335$ $P = 0.001$ n = 28
NT: $R^2 = 0.089$ $P = 0.035$ n = 50
RT: $R^2 = 0.106$ $P = 0.21$ n = 31
ST: $R^2 = 0.51$ $P < 0.001$ n = 28
NT: $R^2 = 0.218$ $P = 0.068$ n = 16
RT: $R^2 = 0.246$ $P = 0.071$ n = 14
ST: $R^2 = 0.738$ $P = 0.062$ n = 5
NT: $R^2 = 0.207$ $P = 0.077$ n = 16
RT: $R^2 = 0.108$ $P = 0.251$ n = 14
ST: $R^2 = 0.521$ $P = 0.169$ n = 5
Tillage
NT
RT
ST


(a)
(b)
SOC Content 0–20cm (g/kg)
MAT
MAP
NT: $R^2 = 0.758$ $P < 0.001$ n = 37
RT: $R^2 = 0.932$ $P < 0.001$ n = 18
ST: $R^2 = 0.655$ $P = 0.027$ n = 7
NT: $R^2 = 0.293$ $P = 0.003$ n = 37
RT: $R^2 = 0.762$ $P < 0.001$ n = 18
ST: $R^2 = 0.886$ $P = 0.013$ n = 7
Tillage
NT
RT
ST