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ORIGINAL ARTICLE

The effect of conservation tillage in managing climate change in arid and semiarid areas—a case study in Northwest China

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Abstract

Climate change and agriculture are strongly related. The management of farmland can influence a variety of agro-ecological processes and affect greenhouse gas (GHG) emission. Based on reported data, this study conducted a meta-analysis to evaluate the role of conservation tillage (CT) in managing climate change in Northwest China. The results indicated that CT significantly improved the concentration of soil organic carbon (SOC), crop yields, and crop water use efficiency (WUE) compared with traditional tillage, and the practices with straw return were significantly higher than those without straw return. With an extended duration of the management, the SOC sequestration of each CT practice showed an increasing trend, but the crop yield did not show an obvious trend. After 5 ~ 10 years and more than 10-year management, CT practices reduced GHG emissions by 5.40 ~ 16.16 t CO_2-eq•ha^{-1} and 8.22 ~ 21.53 t CO_2-eq•ha^{-1} compared to traditional tillage, respectively. In most CT practices, winter wheat-summer maize rotation (W-M) planting pattern had the best SOC sequestration, and spring wheat showed the highest increasing of yield and WUE. More specifically, compared to traditional tillage, the SOC concentration under W-M increased by 10.15 ~ 20.09%, and the yield and WUE under spring wheat increased by 6.87 ~ 17.83% and 8.82 ~ 46.32%, respectively. In conclusion, CT played a positive role in tackling climate change in Northwest China.

Keywords Conservation tillage · Climate change · Soil organic carbon concentration · Crop yield · Crop water use efficiency

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1 Introduction

Northwest China is located in the mid-latitude region of the hinterlands of Eurasia, which is an ecologically fragile area with severe desertification (Yang et al. 2018). Owing to the fragile nature of ecosystem, this region is considered to be one of the most sensitive regions to global climate changes (Xiao and Xiao 2019). Climate changes are affecting its ecological health and ecosystem services (Cheng and Li 2020), such as exacerbating the process of desertification (Wang et al. 2011) and increasing the changes and uncertainty of water systems (Xiao and Xiao 2019). In recent decades, the intensity of human activity in the region has been gradually increasing (Li et al. 2019), but long-term excessive cultivation has led to several environmental issues, such as soil erosion and land degradation (Liu et al. 2018). Owing to the combination of anthropogenic and natural effects (such as drought), the environment of Northwest China has suffered severe degradation (Miao et al. 2016).

Climate change and agriculture are strongly related. Farmland management can influence a variety of agro-ecological processes and affect greenhouse gas (GHG) fluxes. The increasing demand for food has resulted in intensive agricultural practices, which has further aggravated climate change by releasing GHG (Arora 2019). Moreover, it is clear that the fast pace of climate change has had a far-reaching impact on agro-ecosystems and their productivity (IPCC 2019a). Thus, it is highly urgent to adopt effective agricultural production measures to combat the impact of climate change and ensure food security, particularly in this ecologically fragile area.

Conservation tillage (CT) holds substantial potential for the sustainability of agricultural productivity and the environment (Reddy 2016). Studies indicated that CT can save energy and time by reducing the number of tillage operations (Akbarnia and Farhani 2014; Kushwa et al. 2016), sustain crop productivity and enhance profitability (Nawaz et al. 2016; Shahzad et al. 2017), reduce soil erosion (Komissarov and Klik 2020) and loss owing to the protective effect of crop residues that remain in the soil (Vanlauwe et al. 2014), increase the abundance of profitable functional bacteria species (Wang et al. 2016), reinforce carbon and nitrogen sequestration in the soil (Andruschkewitsch et al. 2013; Wu et al. 2019), and reduce GHG emissions (Yeboah et al. 2016; Nawaz et al. 2017).

In 2017, the area in which CT is practiced in China had reached 7584.44 khm^2, and Northwest China is a key region for CT, comprising 36.24% of the total area of China (China Agricultural Machinery Industry Yearbook Editorial Committee and China Agricultural Machinery Industry Association 2019). A number of studies have reported the effects of CT on confronting climate change in Northwest China (Yeboah et al. 2016; Lu and Lu 2017; Wu et al. 2019). However, most studies focus on scattered points, and there is a lack of overall regional studies. Therefore, based on reported data, this study conducted a meta-analysis to systematically evaluate the role of CT in managing climate change from the perspectives of a reduction in GHG by SOC sequestration and an increase in crop yield and WUE in Northwest China. This study can also provide effective references, so that arid and semiarid ecologically fragile regions can manage climate change.

2 Materials and methods

2.1 Site description

According to a study of the division of farming systems that utilized provinces as the unit by Liu and Chen (2005), the Northwest Region includes the Inner Mongolia Autonomous

Region, Xinjiang Uyghur Autonomous Region, Tibet Autonomous Region, Ningxia Hui Autonomous Region, Shanxi, Shaanxi, Gansu, and Qinghai and comprises 58.3% of China's land area (Fig. 1). This region is located in the warm-temperate zone, and the climate is arid or semiarid. Precipitation is very rare with the annual precipitation averaging approximately 200 ~ 550 mm (Liu and Chen 2005). However, the evaporation is extremely high, based on the published literature obtained in this study, we found that the average evapotranspiration is 1.90 ± 0.9 mm•day^{-1} during the crop growth period. Although the scenario prediction indicated that the precipitation in this region would show a weak rising trend in the future, the vulnerability of agricultural production to climate change is still very prominent (Editorial Board of the Third National Assessment Report on Climate Change 2015).

Fig. 1 Northwest Region of China (in red line area)

2.2 Principles of data collection

We searched for peer-reviewed publications from 1980 to July 2020 on CT in Northwest China via the Web of China National Knowledge Internet (CNKI) and Google Scholar. Key indicators included the tested site, test treatments, experimental duration, soil organic carbon (SOC) concentration, bulk density, crop water use efficiency (WUE), crop type, and crop yield which were compiled. In addition, the studies selected also needed to conform to the following criteria: (i) all the treatments had to include conventional tillage as the control; (ii) the starting and ending time of the experiment were clear, and the management remained unchanged during the study period; (iii) the observed value (i.e., SOC, WUE, and crop yield) after the management of each treatment were clear; (iv) the data must have originated from field experiments, and laboratory-based studies were excluded; the area of the treatment was greater than 30 m^2; and (v) the experiments must have been replicated.

Additional procedures were employed to facilitate subsequent analyses. Outliers were identified and removed by a boxplot using SPSS 19.0 (IBM, Inc., Armonk, NY, USA). An outlier is a data point that lies more than one and a half times the length of the box from either end of the box. We digitized the data to present graphs using the software GetData 2.0™ (GetData Pty Ltd., Kogarah NSW 2210, Australia).

The CT that has been implemented in China can be divided into five categories based on published studies: traditional tillage with straw return (TS), reduced tillage without straw return (RT), reduced tillage with straw return (RS), no tillage without straw return (NT), and no tillage with straw return (NS). For details, traditional tillage refers to three or more plows and without straw return; reduced tillage refers to shallowed or reduced plow compared with traditional tillage; no tillage refers to no plow treatment throughout the test period and sowing and fertilizing were done in one time with no tillage planter; and when the amount of returning straw (cover on the soil surface or plow into the soil) exceeds 50%, it was regarded as straw return. This study took traditional tillage as baseline and conducted a meta-analysis on these five CT measures.

2.3 Meta-analysis

The natural log of the response ratio (lnR) was used as a metric of the effect size (Stiling and Cornelissen 2007; Wu et al. 2011), $lnR = \ln(x_t - x_c) = \ln(x_t) - \ln(x_c)$, where x_t and x_c are the means of the treatments and the control, respectively, for a given indicator variable (SOC, WUE, or crop yield). Treatment effects were considered significant if the 95% CI did not overlap with zero (Blankinship et al. 2011).

The data that was composed of soil organic matter was multiplied by 0.58 to convert it to SOC as described by Post et al. (1982). Parts of the datasets did not report standard errors/deviations. To address this obstacle while maintaining a robust meta-analysis, a calculation was made based on the known data (Higgins and Green 2011). In analysis, the experimental duration and crop type were considered to examine the effect sizes of the five CT practices (TS, NT, NS, RT, and RS). The experimental duration was divided into three stages: less than 5 years, 5 to 10 years, and more than 10 years, and this division was applicable to the analysis of SOC concentration and crop yield; data size is shown in Fig. 2A. Four major crop types, including spring wheat, winter wheat, maize, and beans, were selected for crop yield and WUE analysis; data size is shown in Fig. 2B, while the analysis of SOC concentration was carried out on the basis of planting patterns formed by these four crop types, including wheat-maize rotation, wheat-beans rotation, wheat-maize-beans rotation, single wheat and single maize; data size is shown in Fig. 2C. As such, multifactorial studies (i.e., in which tillage treatments were combined with other treatments in a factorial design) and studies that reported results for multiple years contributed more than one comparison to our dataset.

In addition, various management alternatives, such as planting density, crop variety, and meteorological conditions, may interactively have affected the efficacy. Those factors or effects were not included in the meta-analysis, owing primarily to limited observations and/or the impact being relatively minor or inconclusive.

2.4 Evaluation of the mitigation and adaptation effects of CT

The evaluation of the effect of CT on climate change primarily includes the emission reduction and adaptation, and the reduction primarily focuses on the sequestration of SOC, while adaptation primarily focuses on crop yield and WUE. To calculate the effects of emission reduction and adaptation, the results for the analyses on lnR of SOC concentration, crop yield, and WUE were back-transformed and reported as a change in percentage (CP) under CT practices relative to traditional tillage, and the calculation method was CP = [R-1] * 100.

2.4.1 Emission reduction by SOC sequestration

The change of SOC is a long-term process, so the evaluation of the mitigation effect was mainly based on time series. With reference to the IPCC (2006, 2019b), the method of calculation of emission reduction by SOC sequestration under CT in the 0–20-cm soil layer compared with traditional tillage was as follows:

$$\triangle \mathrm{ER}_{\mathrm{soc}\ i} = \triangle SOC_i * BD_i * 0.2 * 10 * \frac{44}{12} \tag{1}$$

where

$\triangle \mathrm{ER}_{\mathrm{soc}\ i}$	represents the emission reduction by SOC sequestration under CT i compared with traditional tillage (t CO_2-eq•ha^{-1});
$\triangle SOC_i$	represents the change of SOC concentration under CT i (g•kg^{-1});
BD_i	represents the average bulk density of CT i (mg•m^{-3});
i	represents the type of CT;
0.2	represents the soil depth (m);
10	represents the unit conversion factor;
44/12	represents the conversion of carbon to CO_2.

$$\triangle SOC_i = \overline{SOC_i} * CP_i \tag{2}$$

where

$\overline{SOC_i}$	represents the average SOC concentration under traditional tillage (g•kg^{-1});
CP_i	represents the percentage change of SOC concentration under CT i relative to traditional tillage (%).

Fig. 2 Data size of each indicator variable. Note: SOC, soil organic carbon; WUE, crop water use efficiency; TS, traditional tillage with straw return; NT, no tillage without straw return; NS, no tillage with straw return; RT, reduced tillage without straw return; RS, reduced tillage with straw return; W-M, wheat-maize rotation; W-B, wheat-beans rotation; W-M-B, wheat-maize-beans rotation; SW, single wheat; SM, single maize; and Ave, average effects

2.4.2 The effects on crop yield

The evaluation of the adaptation effect on crop yield was mainly based on crop type. The crop yield changes of CT practices relative to traditional tillage were calculated as follows:

$$\triangle Y_{i,j} = \overline{Y_{i,j}} * CP_{i,j} \tag{3}$$

where

$\triangle Y_{i,j}$ represents the change of crop *j*'s yield under CT *i* relative to traditional tillage (kg•ha^{-1});
$\overline{Y_{i,,}}$ represents the average yield of crop *j* under traditional tillage (kg•ha^{-1});
$CP_{i,j}$ represents the percentage change of crop yield under CT *i* relative to traditional tillage (%);
i represents the type of CT;
j represents the type of crop.

2.4.3 The effects on WUE

The evaluation of the adaptation effect on WUE was also based on crop type. The changes of WUE under CT practices relative to traditional tillage were calculated as follows:

$$WUE = EY/ET \tag{4}$$

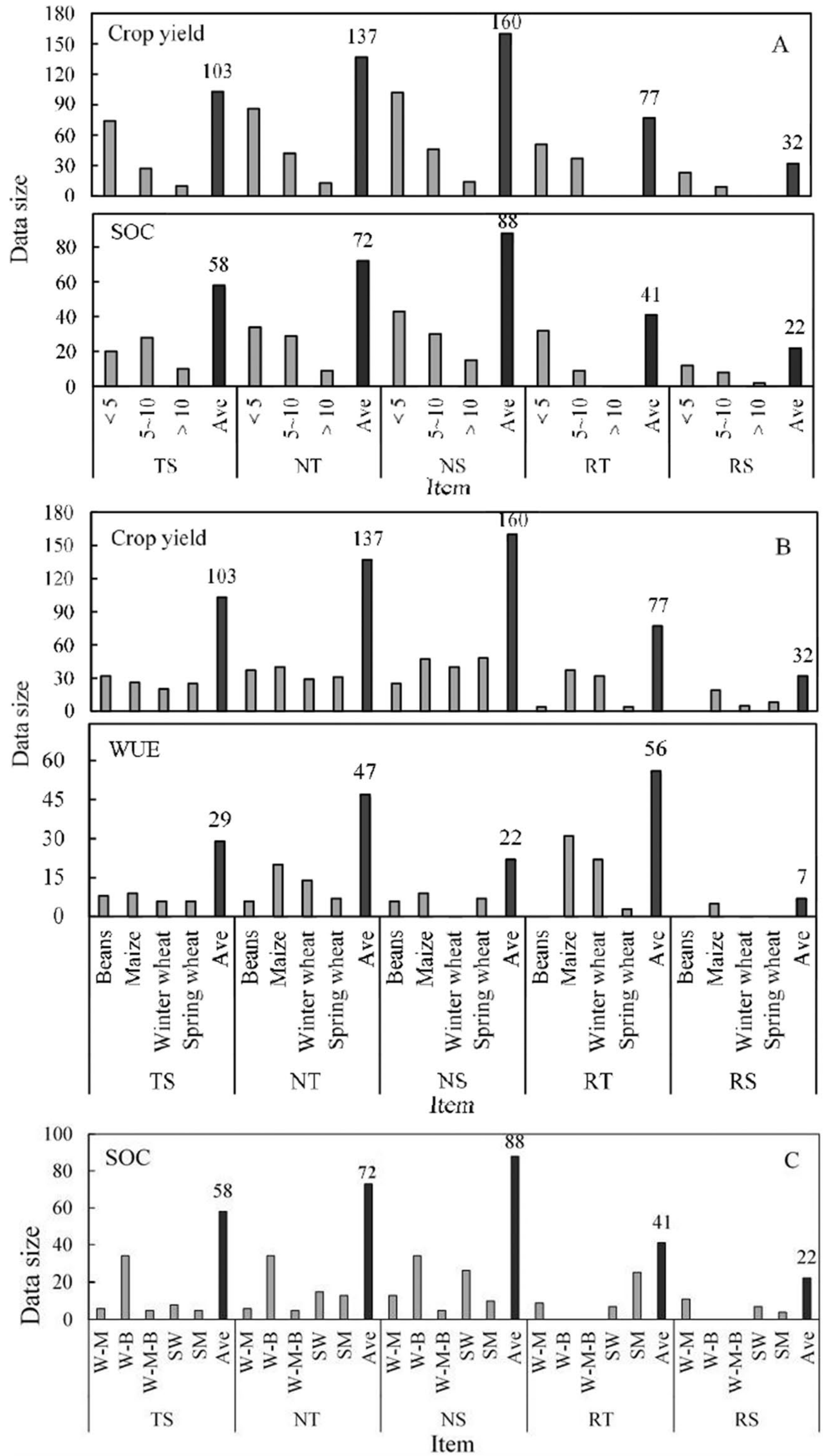
where

WUE represents the crop water use efficiency (WUE, kg·hm^{-2}·mm^{-1});
EY represents the economic yield (kg·hm^{-2});
ET represents the water consumption during crop growth period (mm);

$$\triangle WUE_{i,j} = \overline{WUE_{i,j}} * CP_{i,j} \tag{5}$$

where.

$\triangle WUE_{i,j}$ represents the change of crop *j*'s WUE under CT *i* relative to traditional tillage (kg·hm^{-2}·mm^{-1});
$\overline{WUE_{i,j,}}$ represents the average WUE of crop *j* under traditional tillage (kg·hm^{-2}·mm^{-1});
$CP_{i,j}$ represents the percentage change of WUE under CT *i* relative to traditional tillage (%);
i represents the type of CT;
j represents the type of crop.


A
Crop yield
SOC
Data size
180
150
120
90
60
30
0
80
60
40
20
103
137
160
77
32
58
72
88
41
22
< 5
5~10
> 10
Ave
TS
NT
NS
RT
RS
Item
B
Crop yield
WUE
45
15
29
47
22
56
7
Beans
Maize
Winter wheat
Spring wheat
C
SOC
100
W-M
W-B
W-M-B
SW
SM

2.5 Statistical analysis

The meta-analysis was conducted using Meta win 2.1 (Rosenberg et al. 2000) to identify significant treatment effects. A regression analysis was conducted using SPSS 19.0 to test the relationships between the lnR of SOC concentration and water use efficiency with the lnR of crop yields.

3 Results

3.1 Meta-analysis results

3.1.1 Crop yield

The average lnR of crop yield was RS > NS > RT > TS > NT, and practices with straw return tended to be higher than those without straw return (Fig. 3). The average crop yield of the five CT practices increased significantly compared with traditional tillage.

In NT, RT, and RS, there were no significant differences in the lnR of crop yields under varying durations of experiment, but in TS, the lnR of experimental duration more than 10 years and 5 to 10 years was significantly higher than that of less than 5 years, and in NS, the lnR of experimental duration >10 years was significantly higher than those of less than 5 years and 5 to 10 years. In TS, NS, and RS, the yields of all type of crops were significantly higher than those under traditional tillage. In TS, NT, and RT, winter wheat had the highest yield of the four crops, and the yield increased by 12.14%, 6.87%, and 17.83%, respectively, compared with traditional tillage. The beans in NS had the highest effect on crop yield among all the items, with the value of lnR was 27.38 ± 2.29 (Fig. 3).

3.1.2 Crop water use efficiency

RS had the highest lnR of average WUE, which was significantly higher than those of NT, RT, TS, and NS, and practices with straw return tended to be higher than those without straw return. The average WUE was improved significantly under each CT practice compared with traditional tillage. Spring wheat had the highest WUE in each CT practice, and the WUE increased by 8.82 ~ 46.32% compared with traditional tillage. Winter wheat and maize had the lowest lnR of WUE in RT, TS, and NT, NS, respectively (Fig. 4).

3.1.3 SOC concentration

In general, the average lnR of SOC concentration found that reduced tillage > no tillage > traditional tillage, and the practices with straw return tended to be higher than those without straw return (Fig. 5). The RS had the highest average lnR of 14.84 ± 1.52 (mean ± 95% CI), which was not significantly different from that of NS but was significantly higher than those of TS, NT, and RT. The SOC concentration of the five CT practices increased significantly compared with traditional tillage ($P < 0.05$).

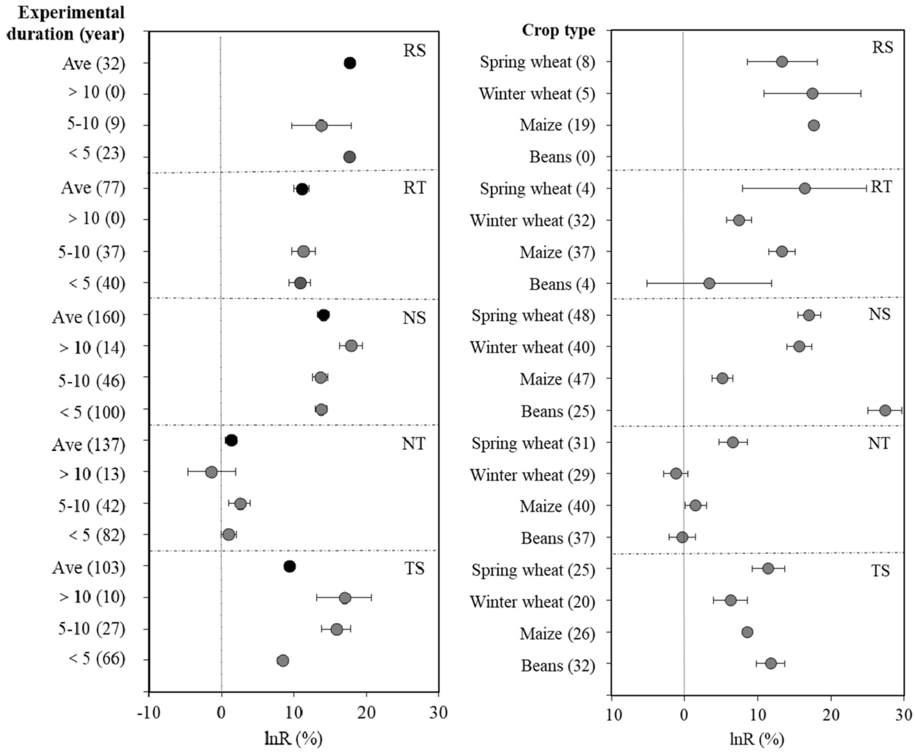


Fig. 3 Crop yield affected by CT practices compared with traditional tillage in **a** experimental duration and **b** crop type. Note: TS, traditional tillage with straw return; NT, no tillage without straw return; NS, no tillage with straw return; RT, reduced tillage without straw return; RS, reduced tillage with straw return; and Ave, average effects. Numbers in brackets are the numbers of comparisons. Treatment effects were significant at $P < 0.05$, when there is no overlap with zero

With an extended duration of the management, the lnR of each CT practice increased. In NT, there were no significant differences in the lnR of SOC concentration among different experimental durations, but the lnRs of experiments that lasted more than 5 years (5 to 10 years or more than10 years) were significantly higher than those that lasted less than 5 years in TS, NS, RT, and RS. The experiments that lasted more than10 years in NS had the highest effect of SOC concentration among all the items, with the value of lnR was 24.15 ± 1.77. Except for NS, W-M had the best SOC sequestration effect in each CT practice, and the SOC concentration increased by 10.15 ~ 20.09% compared with traditional tillage. In NS, there were no significant differences in SOC sequestration among different planting patterns, and the lnR of SOC concentration was maintained at $11.03 \pm 2.07 \sim 14.40 \pm 1.18$ (Fig. 5).

3.2 The emission reduction and adaptation achieved by CT practices

3.2.1 Adaptation effects based on crop yield and WUE

Except for winter wheat and maize under NT and beans under RT, all CT practices significantly increased the yield crops compared with traditional tillage. In general, maize

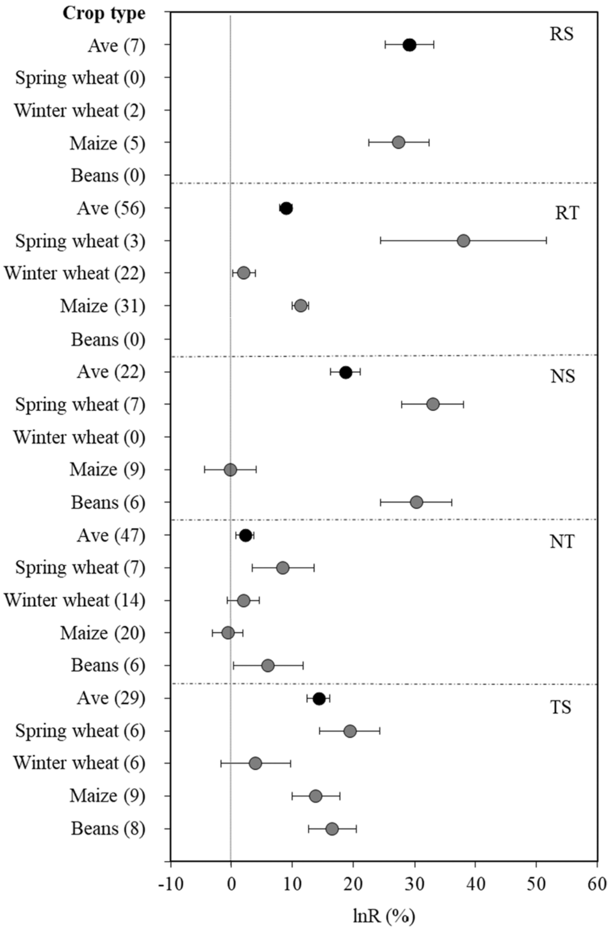


Fig. 4 WUE affected by CT practices compared with traditional tillage in crop type. Note: TS, traditional tillage with straw return; NT, no tillage without straw return; NS, no tillage with straw return; RT, reduced tillage without straw return; RS, reduced tillage with straw return; and Ave, average effects. Numbers in brackets indicate the numbers of comparisons. Treatment effects were significant at $P < 0.05$, when there is no overlap with zero

under RS had the highest increase of yield. For specific crops, spring wheat and beans under NS and winter wheat and maize under RS had the highest yield increasing effect (Table 1).

Except for maize under NT and NS and winter wheat under TS, all CT practices increased the WUE compared with traditional tillage. In general, maize under RS had the highest increase of WUE compared with traditional tillage. For specific crops, spring wheat under RT, winter wheat under TS, maize under RS, and beans under NS had the highest effect on increasing WUE (Table 2).

3.2.2 Emission reduction achieved by SOC sequestration

In general, with the increase in the duration of experiments, the emission reduction achieved by SOC sequestration of NT compared with traditional tillage was relatively stable, and the value remained at 5.40~5.78 t CO_2-eq•ha^{-1}, while that of the other four practices increased. When the experimental duration was less than 5 years, RS had the highest emission reduction compared with traditional tillage and followed by NS, RT, NT, and TS in turn. When the experimental duration was 5 to 10 years, RS had the highest emission reduction, which was

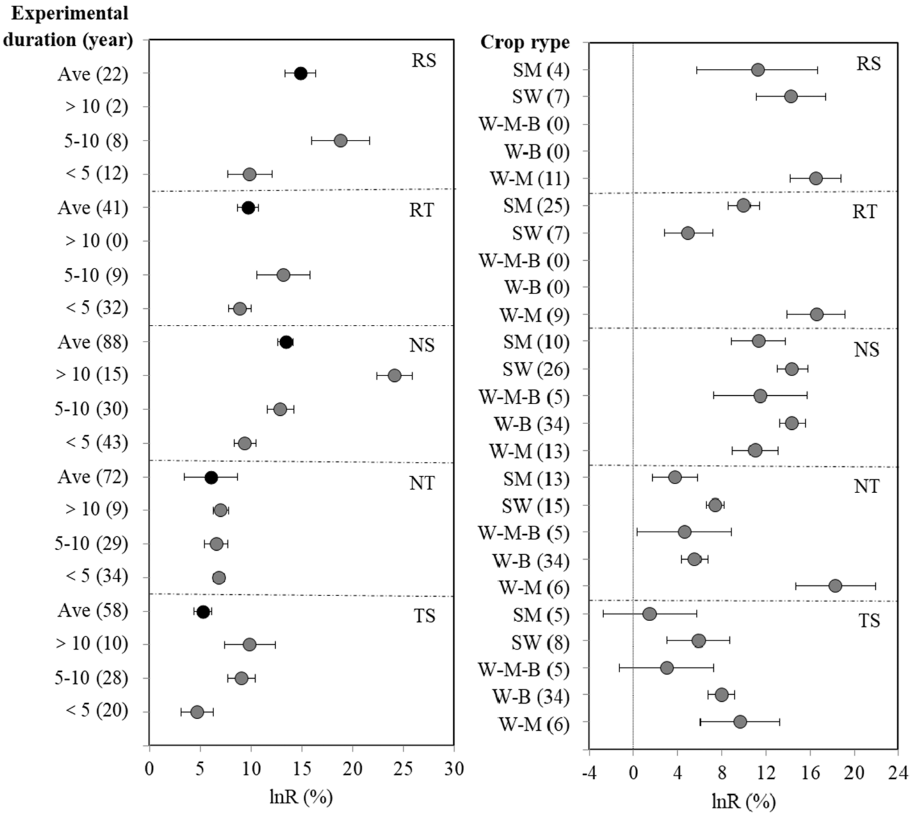


Fig. 5 SOC concentration affected by CT practices compared with traditional tillage in **a** experimental duration and **b** crop type. Note: TS, traditional tillage with straw return; NT, no tillage without straw return; NS, no tillage with straw return; RT, reduced tillage without straw return; RS, reduced tillage with straw return; W-M, wheat-maize rotation; W-B, wheat-beans rotation; W-M-B, wheat-maize-beans rotation; SW, single wheat; SM, single maize; and Ave, average effects. Numbers in brackets are the numbers of comparisons. Treatment effects were significant at $P<0.05$, when there is no overlap with zero

2.14, 2.99, 1.48, and 1.46 times of TS, NT, NS, and RT, respectively. The reduction in emissions of RT and RS was not calculated owing to the lack of data more than 10 years. For the other three practices, NS had the highest reduction in emissions compared with traditional tillage, which was also the highest value of all CT practices under the all the duration of experiments (Table 3).

3.3 Correlation analysis on the effect sizes of CT

Significant relationships were observed between the lnR of crop yield and SOC concentration ($R^2=0.3685$, $P<0.05$) and the lnR of crop yield and WUE ($R^2=0.7254$, $P<0.05$) (Fig. 6). These trends indicated a positive relationship between yield and SOC concentration of and between yield and WUE under CT practices, i.e., the increase in concentration of SOC and water use efficiency may have had positive effects on crop yield under CT.

Table 1 The change in crop yield under CT practices compared with that of traditional tillage (kg•ha^{-1})

Crop type	TS	NT	NS	RT	RS
Spring wheat	337.89 (275.43 ~ 400.36)	191.05 (135.97 ~ 246.13)	517.64 (474.17 ~ 561.10)	496.25 (249.38 ~ 743.13)	397.75 (262.09 ~ 533.41)
Winter wheat	303.15 (191.93 ~ 414.36)	− 55.79 (− 134.56 ~ 22.97)	795.65 (714.98 ~ 876.30)	361.76 (279.19 ~ 444.33)	894.49 (573.88 ~ 1215.10)
Maize	678.20 (626.55 ~ 729.85)	116.71 (2.31 ~ 231.12)	401.67 (293.41 ~ 509.94)	1078.59 (944.18 ~ 1213.01)	1464.92 (1415.56 ~ 1514.29)
Beans	195.40 (164.84 ~ 225.96)	− 4.52 (−33.17 ~ 24.14)	491.37 (455.23 ~ 527.51)	53.31 (−85.10 ~ 191.72)	–

TS, traditional tillage with straw return; *NT*, no tillage without straw return; *NS*, no tillage with straw return; *RT*, reduced tillage without straw return; and *RS*, reduced tillage with straw return. "--" indicates lack of data for analysis. Data in the table represents "mean (95% CI)"

Table 2 The change in WUE under CT practices compared with that of traditional tillage (kg•ha^{-1}•mm^{-1})

Crop type	TS	NT	NS	RT	RS
Spring wheat	0.21 (0.16 ~ 0.27)	0.72 (0.29 ~ 1.14)	3.18 (2.75 ~ 3.60)	3.77 (2.58 ~ 4.95)	–
Winter wheat	0.38 (− 0.17 ~ 0.93)	0.18 (− 0.06 ~ 0.43)	–	0.19 (0.02 ~ 0.36)	–
Maize	2.71 (1.98 ~ 3.43)	− 0.11 (− 0.57 ~ 0.35)	− 0.04 (− 0.83 ~ 0.75)	2.19 (1.95 ~ 2.44)	5.76 (4.84 ~ 6.67)
Beans	0.99 (0.77 ~ 1.21)	0.34 (0.02 ~ 0.67)	1.95 (1.62 ~ 2.27)	–	–

TS, traditional tillage with straw return; *NT*, no tillage without straw return; *NS*, no tillage with straw return; *RT*, reduced tillage without straw return; and *RS*, reduced tillage with straw return. "--" indicates lack of data for analysis. Data in the table represents "mean (95% CI)"

4 Discussion

4.1 The effects of CT on crop yield and water use

The adverse effects of climate change on crop yield have been evident for several years. One of the main threats from climate change arises from the stresses and shocks caused by erratic rainfall, such as water deficit in the soil profile (Lal et al. 2015). This study showed that the yield under each CT practice was significantly higher than that of traditional tillage in terms of average of four crops, and practices with straw return tended to be higher than those without straw return. But it is worth noting that NT had the lowest effect on improving crop yield, and when the experimental duration was more than 10 years or when the crop type was winter wheat and beans, NT showed a decreasing trend in crop yield compared with traditional tillage. Kihara et al. (2011) and Ren et al. (2018) found that the grain yield of NT was significantly reduced compared with traditional tillage. The decrease in crop yield under NT may be related to adverse soil structure that limit the development of plants (Page et al. 2013). However, crop cover can alleviate the adverse effect of NT on crop yields (Nandan et al. 2018). In this study, all crops under NS had positive effect of increasing yield. The increase in

Table 3 The reduction in emission by SOC sequestration of CT practices compared with that of traditional tillage (t CO_2-eq•ha^{-1})

Year	TS	NT	NS	RT	RS
< 5	3.81 (2.53 ~ 5.09)	5.63 (5.16 ~ 6.10)	7.83 (6.99 ~ 8.68)	7.40 (6.51 ~ 8.28)	8.26 (6.50 ~ 10.01)
5–10	7.54 (6.46 ~ 8.61)	5.40 (4.47 ~ 6.32)	10.91 (9.87 ~ 11.96)	11.06 (8.96 ~ 13.17)	16.16 (13.90 ~ 18.43)
> 10	8.22 (6.22 ~ 10.22)	5.78 (5.19 ~ 6.37)	21.53 (20.13 ~ 22.94)	–	–

TS, traditional tillage with straw return; *NT*, no tillage without straw return; *NS*, no tillage with straw return; *RT*, reduced tillage without straw return; and *RS*, reduced tillage with straw return. "--" indicates lack of data for analysis. Data in the table represents "mean (95% CI)"

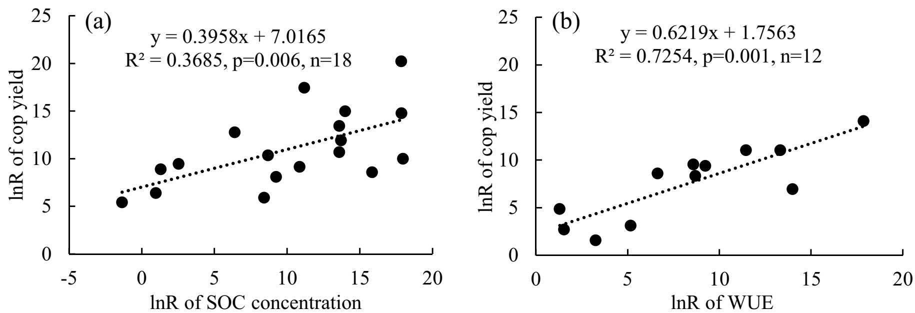


Fig. 6 Relationship between the lnR of the SOC concentration and WUE with lnR of crop yield under CT compared with that of traditional tillage. Note: SOC, soil organic carbon; CT, conservation tillage

crop yields under the straw return, on the one hand, may be related to the improvement of water infiltration under straw return (Page et al. 2013; Sithole et al. 2019); on the other hand, it may be related to the improvement of soil fertility and structure caused by the increase of SOC concentration (Sainju et al. 2002). However, combined with the effects of SOC concentration, we found that, although W-M planting pattern had the highest increasing in SOC concentration under TS, NT, and RT, it had a lower yield increasing effect. These results suggest that increased SOC concentrations are beneficial to crop yields, but do not play a dominant role in arid regions such as Northwest China; instead, the effect of CT practices on soil moisture may be more important. CT can protect soil moisture and increase crop yield by improving soil physical structure and water storage (Li et al. 2020). However, the increase of gravimetric water content and infiltration rate under CT practices is closely related to the improvement of soil porosity caused by the increasing of SOC concentrations (Manhas et al. 2015). This study is an integrated analysis based on the results of published studies. Although it can effectively evaluate the positive effects of CT practices, it cannot reveal the mechanism of the high efficiency. While for more effective agricultural production in arid regions, the relevant mechanism deserves further study.

In arid regions, water deficit was one of the limiting factors of crop yield, but the distribution of precipitation during crop growth period rather than total precipitation was the key factor affecting crop yield (Passioura 2010). CT practices can increase the gravimetric water content and infiltration rate of soil (Manhas et al. 2015), which made moisture to be stored in deeper soil profile and reduced evapotranspiration losses. The stored water was especially valuable because it tends to be accessed during the critical period of yield formation (such as flowering and grain filling), which helps increase crop yields (Passioura 2010). We also found that, under all CT practices, the WUE of spring wheat and beans was higher, while that of winter wheat was lower, which indicated that WUE was related to crop types. Reducing resource and environmental load while increasing grain yield is one of the major challenges for agriculture (Xu et al. 2020). Diversified planting, such as rotation and intercropping, has positive ecological benefits (Chen et al. 2019). However, the yield and water use of different crops in arid regions have different responses to the same management measures (Álvaro-Fuentes et al. 2009). In the process of diversified planting in arid regions, the suitable crops should be selected to achieve the win-win ecological and economic benefits.

4.2 The effects of CT on SOC sequestration

CT practices have been widely considered to be an effective way to reduce the negative impacts of traditional tillage practices on GHG emissions. This study found that CT practices significantly improved the concentration of SOC compared with traditional tillage, and the practices with straw return were significantly higher than those without straw return. Numerous studies also confirmed this conclusion (Hao et al. 2018; Bai et al. 2019; Liu et al. 2019), and the mechanisms maybe attributed to returned straw which provides additional inputs of biomass that increase the inputs of carbon (Blanco-Canqui et al. 2014; Poeplau and Don 2015), improve the basic soil physicochemical and biological properties (Hao et al. 2018; Jha et al. 2020), promote soil aggregation and structure (Sainju et al. 2002), and therefore improve the concentration of SOC (De Baets et al. 2011). Analysis based on crop planting patterns in this study also proved that straw return had positive effects on soil carbon sequestration. W-M planting pattern had the largest amounts of residues and straw return in 1 year and had the highest SOC sequestration effects in TS, NT, RT, and RS. But it is worth noting that W-M had the lowest SOC sequestration effect under NS. We speculated that excessive straw return under no tillage management disturbed soil microbial function and was not conducive to SOC sequestration (Jin et al. 2020). In addition, we found that with an extended duration of the management, the SOC sequestration of each CT practice showed an increasing trend and long-time NS and RS managements had better SOC sequestration. The Northwest China has severe soil erosion, and the SOC on the surface is more vulnerable to erosion (Liu and Chen 2005). NS and RS can reduce the rate of decomposition of soil organic matter by reducing the disturbance of soil (Briones and Schmidt 2017), and the cover of crop straw can reduce the loss in SOC caused by soil erosion (Lal 2005), which may be the reason why long-time RS and NS managements had better effects on SOC sequestration compared with other CT practices.

However, CT practices have significant impacts on GHG emissions, which may diminish the mitigation benefits of potential climate change. Mei et al. (2018) found that CT significantly increased soil N_2O emissions compared with traditional tillage. Niu et al. (2019) indicated that the 3-year NT stimulated emissions of N_2O primarily by increasing denitrification. In this study, owing to the lack of sufficient data, the impact of CT on soil GHG emissions was not analyzed. The higher variability in GHG emissions in soils under differing farming methods has necessitated further study under soil- and site-specific conditions (Yeboah et al. 2016). However, in Northwest China, there are few studies on the emission reduction effect of CT practices based on the comprehensive effects of SOC sequestration and GHG emissions, and it is necessary to carry out systematic long-term positioning research.

4.3 Limitation of the study and improvement needed

This study clarified the mitigation and adaptation effect size of five typical CT practices, which show promise for effectively addressing climate change in Northwest China. However, there are still some deficiencies in this study. First, the effects size may be synthesized with uncertainties due to the inherent limitations of methodologies used in such analyses and/or of data quality deficiencies among different studies. Although this study is carried out in the Northwest China with similar climatic characteristics, there is still some heterogeneity among different research results, e.g., different soil characteristics, fertilization management, and methods of straw disposal, also influenced the effect of CT in SOC sequestration, crop yield, and WUE. Nevertheless, together with the relatively rigorous principles of data collection and the identification and elimination of outliers, the method of meta-analysis offered a powerful statistical analysis, and these uncertainties might be unlikely to change the responses of CT in managing climate change. Second, CT practices have significant impacts on GHG emissions (Niu et al. 2019), which may diminish the mitigation benefits of potential climate change. Besides, soil and land degradation are major ecological challenges in Northwest China (Liu et al. 2018), and both are important causes of the loss of soil carbon and a decline in the quality of cultivation (Sun et al. 2017). However, the above three aspects of GHG emissions in Northwest China were not addressed in this study, which is the limitation. Further research to fully reveal the effect of CT in addressing climate change should be conducted.

5 Conclusions

Conservation tillage played a positive role in tackling climate change, which significantly improved the concentration of SOC, crop yields, and WUE compared with traditional tillage, and the practices with straw return were significantly higher than those without straw return. With an extended duration of the management, the SOC sequestration effect of each CT practice showed an increasing trend, but the crop yield did not show an obvious trend. The W-M planting pattern had the best SOC sequestration under all CT practices except for NS, and spring wheat showed the highest yield increase and WUE under most CT practices.

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