https://doi.org/10.17221/396/2021-PSE

Rotary and subsoiling tillage rotations influence soil carbon and nitrogen sequestration and crop yield

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Citation: Zhu S.W., Gao T.P., Liu Z., Ning T.Y. (2022): Rotary and subsoiling tillage rotations influence soil carbon and nitrogen sequestration and crop yield. Plant Soil Environ., 68: 89–97.

Abstract: Long-term single tillage causes serious deterioration of land quality and reduction of crop yield. Tillage rotation can alleviate the problems caused by long-term single tillage. However, the effects of different tillage rotations are still very limited. A tillage rotation experiment was conducted in the North China Plain to evaluate the impacts of tillage rotation on soil organic carbon (SOC), soil total nitrogen (STN) and crop yield. There were eight treatments with two main factors: tillage practice (four types: rotary tillage (R, 2002–2017), subsoiling tillage (S, 2002–2017), rotary to subsoiling tillage (RS, 2015–2017) and subsoiling to rotary tillage (SR, 2015–2017)) and straw management (two types: straw return (F) and straw removal (0)). RSF treatment yielded the highest SOC, at 12.53 g/kg. RSF significantly increased SOC by 41.4% compared to RF, while SRF significantly reduced SOC by 11.1% compared to SF. In addition, RSF significantly increased STN content by 21.7% compared with that under RF. Compared with SF, SRF promoted the uniform distribution of soil nitrogen in the 0–20 cm soil layer. Among the treatments, the RSF treatment yielded the highest SOC stock (SOC_S) and STN stock (STN_S), which were 67.68 t/ha and 6.63 t/ha, respectively. Compared with RF treatment, RSF treatment greatly increased SOC_S, by 31.7%. Both tillage rotation treatments increased STN_S by 13.3% under RSF compared to RF, and by 2.3% under SRF compared to SF. In 2016, the annual yield was highest under RSF treatment at 19.80 t/ha. In 2017, the annual yield was highest under SF treatment at 21.37 t/ha, and next highest under RSF at 20.94 t/ha. In summary, long-term rotary tillage followed by subsoiling tillage combined with straw return (RSF) can significantly increase SOC, STN and crop yield. The rotation of rotary tillage to subsoiling tillage combined with the straw return is an effective measure for improving soil quality and increasing crop yields in the North China Plain.

Keywords: tillage conversion; tillage combination; C:N ratio; high productivity

Soil degradation caused by intensive agricultural management has attracted widespread attention which is threatening climate change, food security and ecosystem services (Paustian et al. 2016). Soil organic carbon (SOC) can be used as an ideal indicator to assess soil quality and health. The SOC content affects the potential for the sequestration of soil nutrients, especially nitrogen (N), by altering cation exchange capacity and mineralisation-immobilisation turnover (Maltas et al. 2013). Enhancing soil N retention is beneficial for decreasing fertiliser application, reducing the risk of soil acidification and maintaining soil productivity (Guo et al. 2010). In addition, crop residues play an important role in

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Supported by the Special Research Funding for Public Benefit Industries (Agriculture) of China, Project No. 201503121-05; by the Shandong Major Science and Technology Innovation Projects, Project No. 2019YQ014, and by the Funds of Shandong "Double Tops" Program.

SOC and N management and the improvement of soil quality (Guo and Wang 2013, Dikgwatlhe et al. 2014).

The North China Plain (NCP) is one of the most important grain-producing regions in China. Rotary tillage has been widely used in the NCP (Shi et al. 2016). Tillage in the agricultural system operates directly on the soil and has great influences on the contents of SOC and soil total nitrogen (STN) (Guo et al. 2019). Long-term use of rotary tillage has a negative impact on soil carbon (C), leading to serious soil degradation and crop yield decline (Tian et al. 2016, Hu et al. 2021). Rotary tillage greatly reduces soil aggregate stability, enhances microbial biomass turnover and accelerates organic matter decomposition (Wulanningtyas et al. 2021). Furthermore, subsoiling can improve the planting environment by loosening the subsoil and maintaining a deep tillage layer without overturning (Wang and Li 2014). Many studies have shown that subsoiling can increase SOC and total nitrogen contents and increase crop yield (Xu et al. 2019, Feng et al. 2020, Wang et al. 2020, Xie et al. 2020). Although subsoiling has many benefits, its cost is higher than those of other tillage methods, and its effect on increasing crop yield is not always significant (He et al. 2017). He et al. (2007) showed that annual subsoiling in dryland areas of northern China is uneconomical and unwarranted.

Whether it is possible to use a combination of different tillage methods, leveraging the advantages of various methods, to solve the problems of single tillage is of interest, and the potential use of such an approach to establish a high-productivity, low-energy consumption and sustainable agricultural ecosystem has become a new research direction. A three-year tillage rotation experiment in the Loess Plateau area of China showed that no tillage-subsoiling-no tillage and subsoiling-no tillage-subsoiling rotations significantly increased the contents of organic carbon, total nitrogen and water-stable aggregates in the 0–40 cm soil layer compared with those under plowing (Hou et al. 2013). Lü et al. (2015) found that compared with plowing, the combination of no-tillage, subsoiling and plowing increased the organic carbon and total nitrogen contents in the 0–60 cm soil layer and that compared with continuous no-tillage, the combination promoted the uniform distribution of soil nutrients in the tillage layer and below. Tillage practice rotations change the soil particle size and pore distribution and thus affect the physical and chemical properties of soil to influence crop growth (Tian et al. 2016). Currently, there are few trials of tillage rotation. This study was focused on the short-term impacts of tillage rotation after long-term rotary tillage and subsoiling tillage. The impacts of tillage rotation on farmland soil and crops were assessed by analysing SOC, total nitrogen, and crop yield.

MATERIAL AND METHODS

Site description. The experiment was carried out at the Agronomy Experimental Station of Shandong Agricultural University in Tai'an City, Shandong province. The study site was located at 36°09'30.78–36°09'27.59N and 117°09'13.79–117°09'12.02E. The area had a temperate continental monsoon climate with an average rainfall of 565.7 mm and an average temperature of 15.44 °C from October 2015 to October 2017. Meteorologic data during the study are shown in Figure 1. The soil is classified as Cambisols (FAO-UNESCO 1988). The physical and chemical properties of the soil in 2002 are presented in Table 1.

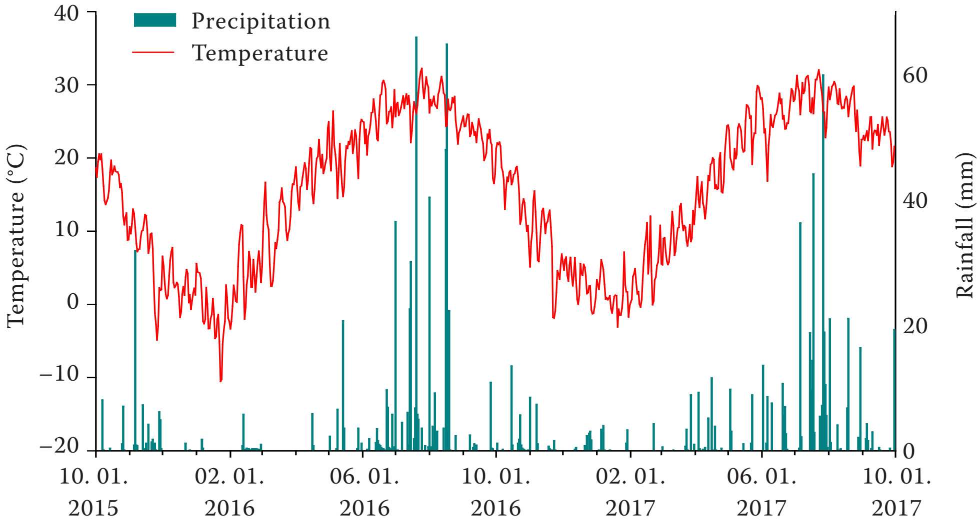

Figure 1. Daily precipitation and average temperature from October 2015 to October 2017

Table 1. Initial soil characteristics in the 0–20 cm layer in 2002

Physical property		Chemical property	
Sand (%)	40	soil organic carbon (g/kg)	7.19
Silt (%)	44	total nitrogen (g/kg)	1.13
Clay (%)	16	total potassium (g/kg)	2.16
Bulk density (g/cm^3)	1.35	total phosphorus (g/kg)	8.09
pH	7.09	available nitrogen (mg/kg)	108.8

Experimental design. The experiment employed a randomised block design and included two factors: tillage practice and straw management. Continuous rotary tillage (R) and subsoiling (S) treatments were established in 2002 and maintained until 2017 (Figure 2). In 2015, half of the plots were converted from subsoiling to rotary tillage (SR) and from rotary tillage to subsoiling (RS). Straw management had two levels: straw removal (0) and straw return (F). Approximately 11 t/ha wheat and 10 t/ha maize residue every year were input continuously into the field after grain harvest in residue retention systems. Straw removal entailed the manual cutting off of wheat and maize straw above the soil surface and its removal from the field. There were eight treatments: R0, S0, RS0, SR0, RF, SF, RSF and SRF. The experiment included eight treatments with three replications. Each replication (plot) was 60 m^2 (15 m × 4 m) in area. Protective zones between each plot were set up. The tillage operations were carried out annually in October before wheat sowing. The details of each tillage mode were as follows: RT – tillage to a depth of 12 cm using a rotavator with an 89 kW tractor; ST – tillage to a depth of 35–40 cm using a vibrating shank subsoiler (with shanks spaced 50 cm apart) powered with a 118 kW tractor. A winter wheat-summer maize double cropping system was used. The tested cultivars were Jimai 22 for wheat and Zhengdan 958 for maize. Straw was defined as the aboveground biomass excluding grains. The field management was consistent across the treatments. During the winter wheat season, 225 kg N/ha, 78.6 kg P/ha and 74.7 kg K/ha were applied as the basal fertiliser, and 100 kg N/ha was top-dressed at the jointing stage with 75 mm of irrigation. During the summer maize season, 120 kg N/ha, 52.4 kg P/ha and 41.5 kg K/ha were applied as basal fertiliser, and 120 kg N/ha was top-dressed at the jointing stage. No irrigation was used throughout the maize growth period.

Soil sampling and analysis. Soil samples were collected from the 0–10, 10–20, 20–30 and 30–40 cm soil layers, with three replications per plot, when maize was harvested in 2016 and 2017. Each soil sample was air-dried, finely ground and passed through a 2 mm sieve after thorough mixing. SOC was determined by the potassium dichromate heating method, and total N was determined by the Kjeldahl method (Bao 2000). Undisturbed soil samples were collected to determine the bulk density in the same soil layers. The SOC stock and STN stock were calculated according to the following formulas (Ding et al. 2012):

$$SOC_S = \Sigma\ (C_i \times \rho_i \times T_i) \times 10^{-1}$$

$$STN_S = \Sigma\ (N_i \times \rho_i \times T_i) \times 10^{-1}$$

where: SOC_S – C pool (t/ha); C_i – SOC concentration (g/kg); STN_S – N pool (t/ha); N_i – TN concentration (g/kg); ρ_i – soil bulk density (g/cm^3); T_i – soil layer thickness (cm); i – soil layer.

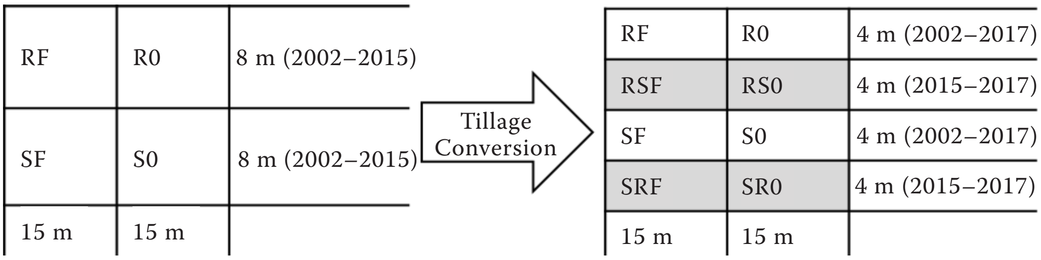

Figure 2. Design of experimental treatments: continuous rotary tillage (R) and subsoiling (S) treatments were established in 2002 and maintained until 2017. In 2015, half of the plots were converted from subsoiling to rotary tillage (SR) and from rotary tillage to subsoiling (RS); straw management: F – straw return; 0 – straw removal

Grain sampling and analysis. Grain samples were collected when the wheat and maize were harvested in 2016 and 2017. The winter wheat samples were obtained from a 1 m^2 area in the centre of each plot, with three replications. The summer maize samples were collected in two rows of 5 m length in the centre of each plot, with three replications. The samples were threshed after air-drying, oven-dried at 65 °C for 48 h, and then weighed.

Statistical analysis. Analysis of variance (ANOVA; SPSS for Windows, version 17.0, Chicago, USA) was used to identify significant differences among treatments, and the significance level was $\alpha = 0.05$. Multiple comparisons were performed using the least significant difference (*LSD*) test to determine the significance of treatment effects. SigmaPlot 10.0 software (Chicago, USA) was used to create figures.

RESULTS

Soil organic carbon content. Among the treatments, the RSF treatment yielded the highest SOC, followed by the SF treatment (Figure 3). In 2016, compared with R0, RS0 increased the SOC in the 20–40 cm soil layer by 53.9%. Furthermore, compared with S0, SR0 significantly reduced the SOC in the 0–40 cm soil layer by 16.9%. RSF significantly increased the SOC in the 0–40 cm soil layer by 36.5% compared with that under RF. Compared with SF, SRF increased the SOC in the topsoil but reduced the SOC in the deep soil. In 2017, regardless of whether the straw was returned, RS significantly increased the SOC by 28.0% compared with that under R, while SR significantly reduced the SOC by 20.6% compared with that under S.

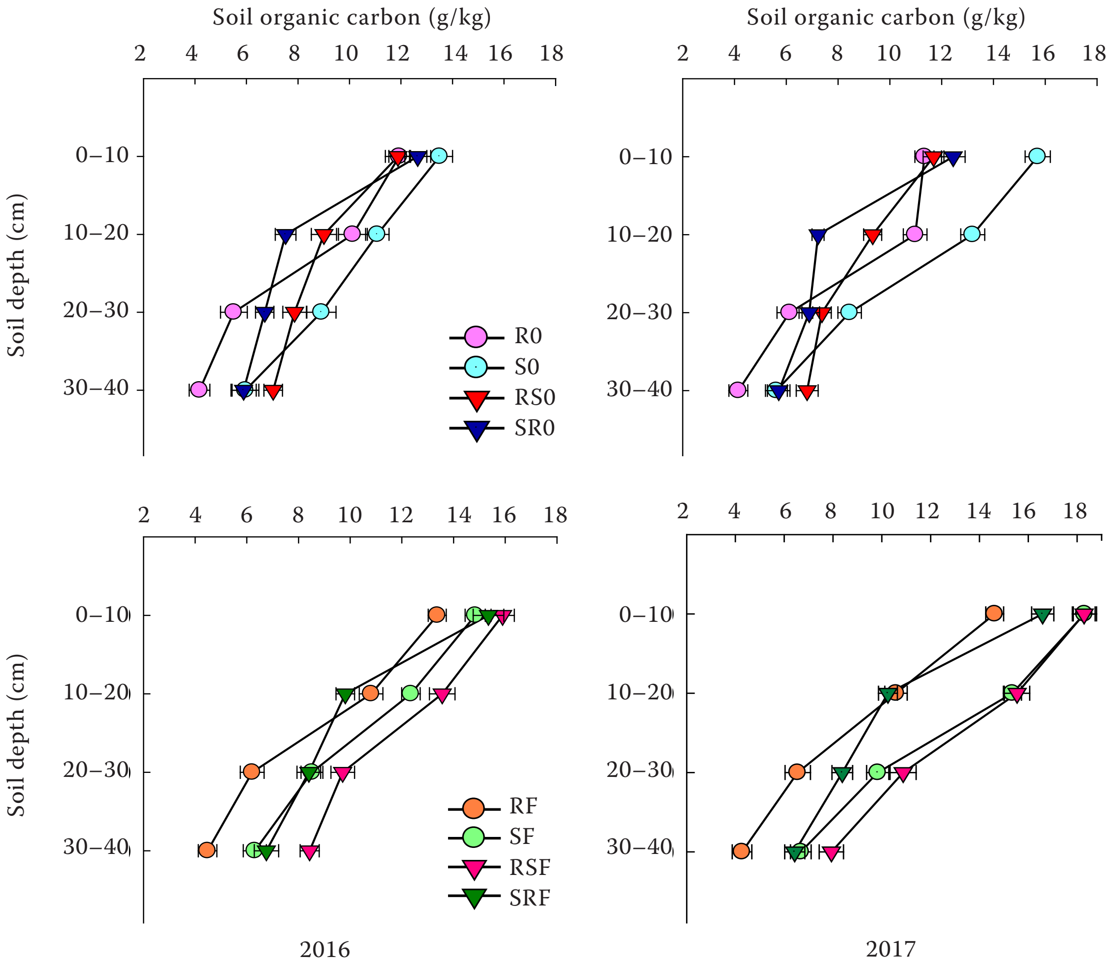

Figure 3. Soil organic carbon distribution in the 0–40 cm layer under different treatments in 2016 and 2017. R0 – rotary tillage with straw removal; S0 – subsoiling tillage with straw removal; RS0 – rotation of rotary to subsoiling tillage with straw removal; SR0 – rotation of subsoiling to rotary tillage with straw removal; RF – rotary tillage with straw return; SF – subsoiling tillage with straw return; RSF – rotation of rotary to subsoiling tillage with straw return; SRF – rotation of subsoiling to rotary tillage with straw return

Soil total nitrogen content. The RSF treatment yielded the highest STN content in the 0–40 cm soil layer, at 1.23%, followed by SF and SRF, at 1.19% and 1.17%, respectively (Figure 4). Under the condition of straw removal, RS0 increased the STN content by 16.1% compared with that under R0. Compared with S0, SR0 reduced the STN content by 21.3%. Under the condition of straw return, RSF significantly increased the STN content, increasing it by 21.7%, compared with that under RF. Compared with SF, SRF promoted the uniform distribution of soil nitrogen in the 0–20 cm soil layer.

Soil organic carbon stock, soil total nitrogen stock and C:N ratio. Among the treatments, the RSF treatment yielded the highest SOC_S and STN_S, which were 67.68 t/ha and 6.63 t/ha, respectively; the SR0 treatment yielded the lowest, at 45.53 t/ha and 4.63 t/ha, respectively (Table 2). SR0 treatment decreased SOC_S by 19.0% compared with that under S0. Compared with RF, RSF treatment greatly increased SOC_S by 31.7%. SRF treatment reduced SOC_S by 7.4% compared with that under SF. RS0 increased STN_S by 9.6% compared with that under R0, and SR0 decreased it by 19.4% compared with that under S0. Compared with RF, RSF increased STN_S by 13.3%.

Crop yields. In 2016, the wheat yield was highest under the SF treatment, at 8.64 t/ha, and maize yield and annual yield were highest under the RS treatment, at 11.41 and 19.80 t/ha, respectively (Figure 5). In 2017, the wheat, maize and annual yields were highest under the SF treatment, at 7.81, 13.56 and 21.37 t/ha, respectively, followed by the RSF treatment, at 7.61, 13.33 and 20.94 t/ha, respec-

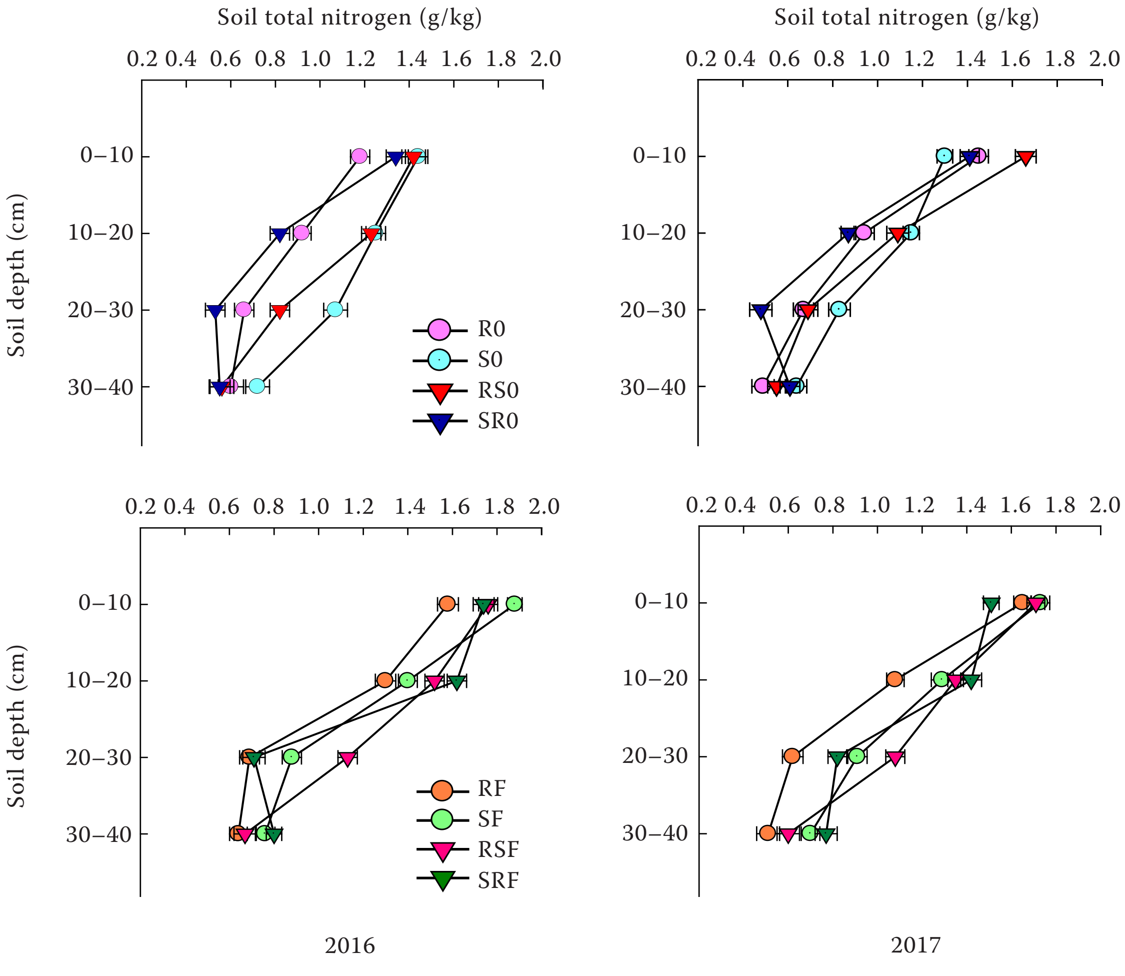

Figure 4. Soil total nitrogen distribution in the 0–40 cm layer under different treatments in 2016 and 2017. R0 – rotary tillage with straw removal; S0 – subsoiling tillage with straw removal; RS0 – rotation of rotary to subsoiling tillage with straw removal; SR0 – rotation of subsoiling to rotary tillage with straw removal; RF – rotary tillage with straw return; SF – subsoiling tillage with straw return; RSF – rotation of rotary to subsoiling tillage with straw return; SRF – rotation of subsoiling to rotary tillage with straw return

Table 2. Soil organic carbon stock (SOC_S), soil total nitrogen stock (STN_S) and the C:N ratio in the 0–40 cm layer in different treatments in 2016 and 2017

Year	Treatment	Bulk density (g/cm^3)	SOC	STN	SOC_S	STN_S	C:N ratio
			(g/kg)		(t/ha)		
2016	R0	1.44^{a}	7.94^{d}	0.84^{d}	45.72^{c}	4.84^{e}	9.45^{b}
	S0	1.39^{abc}	9.86^{b}	1.12^{b}	54.84^{b}	6.23b^{c}	8.81^{c}
	RS0	1.38^{abc}	8.95^{c}	1.01^{c}	49.40^{c}	5.56^{d}	8.88^{c}
	SR0	1.39^{abc}	8.19^{cd}	0.81^{d}	45.55^{c}	4.50^{e}	10.11^{a}
	RF	1.43^{ab}	8.72^{cd}	1.05^{bc}	49.86^{c}	6.02^{cd}	8.28^{d}
	SF	1.34^{c}	10.51^{b}	1.23^{a}	56.31^{b}	6.59^{bc}	8.54^{d}
	RSF	1.34^{c}	11.90^{a}	1.27^{a}	63.78^{a}	6.81^{a}	9.37^{b}
	SRF	1.37^{bc}	10.08^{b}	1.22^{a}	55.24^{b}	6.67^{bc}	8.28^{d}
2017	R0	1.46^{ab}	8.15^{d}	0.89^{cd}	47.60^{d}	5.18^{cd}	9.18^{d}
	S0	1.34^{e}	10.75^{b}	0.98^{bc}	57.59^{bc}	5.25^{cd}	10.96^{ab}
	RS0	1.36^{de}	8.81^{c}	1.00^{b}	47.90^{d}	5.43^{c}	8.83^{e}
	SR0	1.41^{bc}	8.07^{d}	0.84^{d}	45.51^{d}	4.75^{d}	9.58^{c}
	RF	1.47^{a}	9.01^{bc}	0.97^{bc}	52.95^{c}	5.67^{bc}	9.33^{d}
	SF	1.33^{e}	12.54^{a}	1.16^{a}	66.71^{a}	6.16^{ab}	10.83^{b}
	RSF	1.36^{e}	13.16^{a}	1.19^{a}	71.58^{a}	6.45^{a}	11.10^{a}
	SRF	1.41^{cd}	10.41^{a}	1.13^{a}	58.73^{b}	6.37^{a}	9.21^{d}

R0 – rotary tillage with straw removal; S0 – subsoiling tillage with straw removal; RS0 – rotation of rotary to subsoiling tillage with straw removal; SR0 – rotation of subsoiling to rotary tillage with straw removal; RF – rotary tillage with straw return; SF – subsoiling tillage with straw return; RSF – rotation of rotary to subsoiling tillage with straw return; SRF – rotation of subsoiling to rotary tillage with straw return. Different lowercase letters within a column indicate significant differences between treatments ($P < 0.05$)

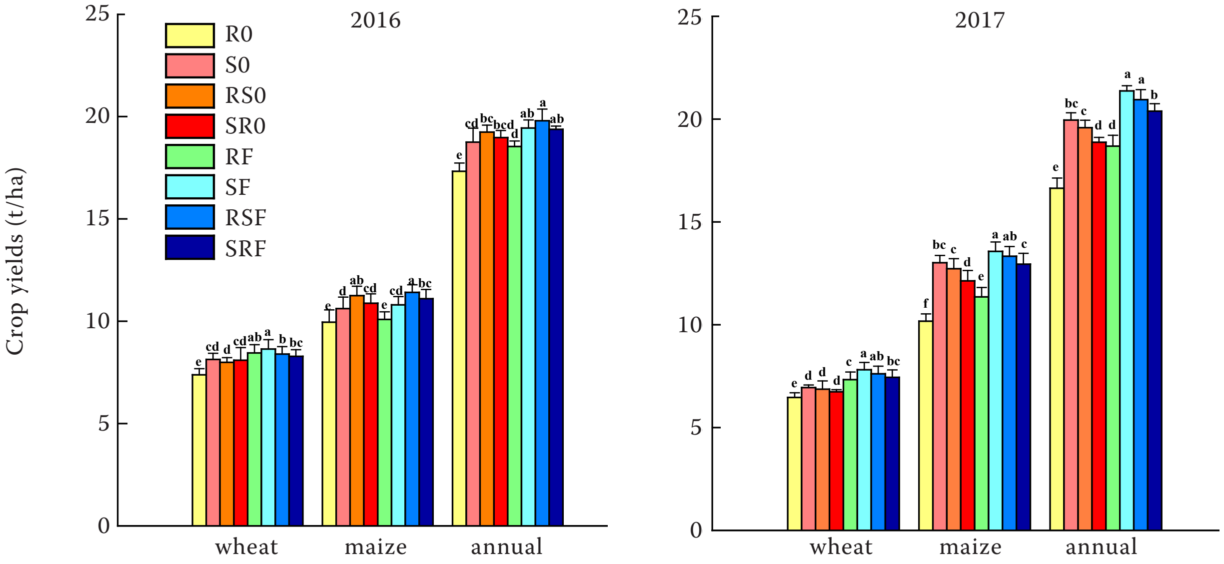

Figure 5. Wheat yield, maize yield and annual yield under different treatments in 2016 and 2017. Different letters within a group indicate significant differences between treatments ($P < 0.05$). R0 – rotary tillage with straw removal; S0 – subsoiling tillage with straw removal; RS0 – rotation of rotary to subsoiling tillage with straw removal; SR0 – rotation of subsoiling to rotary tillage with straw removal; RF – rotary tillage with straw return; SF – subsoiling tillage with straw return; RSF – rotation of rotary to subsoiling tillage with straw return; SRF – rotation of subsoiling to rotary tillage with straw return

tively. In 2016 and 2017, RSF treatment increased wheat, maize and annual yields by 1.4, 15.4 and 9.5%, respectively, compared to those under RF. SRF treatment reduced the wheat, corn and annual yields by 4.4, 1.3 and 2.6%, respectively, compared with those under SF.

DISCUSSION

Effects of tillage rotation on SOC. The tillage rotation treatments in this study significantly changed SOC and SOC_S, with opposite trends observed between the two types of rotation. The rotation from rotary tillage to subsoiling significantly increased SOC and SOC_S in the 0–40 cm soil layer, while the rotation from subsoiling to rotary tillage decreased these parameters. These results may reflect the protective effect of soil aggregates on organic carbon. The RS treatment significantly reduced the artificial disturbance to the topsoil and the damage to soil macro-aggregates. Soil macro-aggregates provide good physical protection for organic carbon (Zhao et al. 2021). In addition, RS broke the plough bottom, reduced soil compaction and bulk density, improved soil porosity, and was conducive to the downward growth of crop roots (Shu et al. 2015, Wang et al. 2019, Li et al. 2020). The increases in root biomass and exudates due to this type of rotation increase nutrient availability to microorganisms, thereby promoting soil carbon sequestration (Cai et al. 2014). In addition, in 2016, compared to R0, RS0 reduced the organic carbon of the 0–20 cm soil layer, while RSF increased it compared to the level under RF. In the 20–40 cm soil layer, RS increased SOC compared to that under R, but the increase differed depending on whether the straw was returned, with RSF and RS0 increasing SOC by 71.7% and 46.0%, respectively. Therefore the rotation of rotary tillage to subsoiling tillage combined with straw return can better preserve SOC than other managements, and the two practices complement each other (Li et al. 2021). Others, in 2016, SRF increased the SOC in the 0–10 cm soil layer compared to that under SF. This result may have been observed because rotary tillage can help incorporate and evenly disperse straw into the soil. By incorporating straw in this manner, the contact area between the straw and soil is increased, which not only accelerates straw decomposition but also improves the metabolic activities of soil microorganisms (Zhou et al. 2020). Therefore, the rotation of rotary tillage to subsoiling can increase soil organic carbon.

Effects of tillage rotation on STN and STN_S. Farmland management measures (tillage methods, straw return, etc.) have a greater impact on soil total nitrogen. An experiment by Wang et al. (2020) on the Loess Plateau in China showed that long-term chisel plough tillage in dryland agroecosystems could serve as a promising soil management practice for increasing crop productivity and maintaining sustainability by enhancing N removal from crop biomass and decreasing N losses *via* N_2O emission and nitrate-N leaching. Tillage-induced variation in STN content may be associated with the change in soil microbial activity under different tillage modes (Butterbach-Bahl et al. 2013). Subsoiling has significantly reduced disturbance to the surface soil compared to rotary tillage. The reduction of tillage intensity reduces soil disturbance and promotes the activity of soil microorganisms, thereby transferring more nitrogen from crop straws to the soil (Qi et al. 2018). Therefore, the rotation of rotary tillage to subsoiling combined with straw return can increase soil total nitrogen in the 0–20 cm soil layer. Because subsoiling loosens and maintains a deep tillage layer without overturning. Meanwhile, rotary tillage cuts, breaks, and blends the soil during the rotation process, and the surface soil is fully mixed. Thus, the distribution of STN under the rotation of subsoiling to rotary tillage is more homogeneous in the 0–20 cm soil layer compared to subsoiling.

Effects of tillage rotation on crop yields. Crop yield is the result of many factors including meteorologic factors (temperature, precipitation, etc.) and farmland management methods (tillage methods, straw return, etc.). High production was maintained under the SF and RSF treatments, as shown by the annual yields. High SOC and STN can ensure a high crop yield. Under a given set of weather conditions, an increase in SOC and STN accumulation can enhance crop production by maintaining soil structure and moderating soil microbial activities (Butter-Bahl et al. 2011, Ghimire et al. 2017). Liu et al. (2020) found that the two-year average yields of wheat and maize under rotary tillage plus subsoiling treatment were increased by 11.3% and 0.7%, respectively, compared with those under continuous rotary tillage treatment. A four-year tillage rotation experiment by Tian et al. (2016) in North China showed that deep tillage altered SOC pools by 15.6 t/ha and decreased subsoil density, thereby benefitting root growth and improving the annual total yield of the wheat and maize cropping system by 24% compared with that obtained under rotary tillage. Moreover, subsoiling in soils with root restriction layers can reduce soil bulk density and improve soil water and nutrient contents and distributions, thereby facilitating root growth and development and increased yield (Figuerola et al. 2012, Schneider et al. 2017). This is similar to our study results. RS significantly increased wheat, maize, and annual yields. In summary, long-term rotary tillage followed by subsoiling combined with straw return can significantly increase SOC, STN and crop yields. The rotation of rotary tillage to subsoiling combined with the straw return is an effective measure for improving soil quality and increasing crop yields in the NCP.

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Received: September 4, 2021
Accepted: January 17, 2022