Optimized straw interlayer improves organic carbon and total nitrogen in soil profile: A four-year experiment in a saline soil

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Abstract

Soil salinization is a critical environmental issue restricting agricultural production. Straw deep returning as interlayer (40 cm) has been a popularized practice to alleviate salt stress. However, the legacy effects of straw interlayer associated with the straw input amount on soil organic carbon (SOC) and total nitrogen (TN) in saline soil remain unclear. Therefore, a four-year (2015-2018) field experiment was conducted with four levels (i.e., 0, 6, 12 and 18 Mg ha $^{-1}$) of straw returning as interlayer. Compared with no straw interlayer (CK), straw interlayers increased SOC content by 14-32% and 11-57% in 20-40 cm and 40-60 cm, respectively. Lower increases were for soil TN content (8-22% in 20-40 cm and 6-34% in 40-60 cm) than SOC content, which led to increase soil C:N ratio in the 20-60 cm soil depth. Compared with CK, remarkable increases of SOC and soil TN contents in 20-60 cm led to the decrease of stratification ratios (0-20: 20-60 cm), which promoted uniform distributions of SOC and TN in soil profiles. Even though soil parameters ranged widely according to the straw input, straw interlayer with 12 Mg ha $^{-1}$ had higher SOC, TN, C:N ratio, and lower soil stratification ratio in 2015-2017, which contributed to salt leaching, water retention, and yield increment. These results highlighted the legacy effects of straw interlayers maintained more than four years, which led to an underestimation for previous short-term experiments, and demonstrated a great potential for subsoil fertility and salt-affected soil amelioration.

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Running Title:

SOC and TN in saline soil

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Abstract:

Soil salinization is a critical environmental issue restricting agricultural production. Straw deep returning as interlayer (40 cm) has been a popularized practice to alleviate salt stress. However, the legacy effects of straw interlayer associated with the straw input amount on soil organic carbon (SOC) and total nitrogen (TN) in saline soil remain unclear. Therefore, a four-year (2015-2018) field experiment was conducted with four levels (i.e., 0, 6, 12 and 18 Mg ha^{-1}) of straw returning as interlayer. Compared with no straw interlayer (CK), straw interlayers increased SOC content by 14-32% and 11-57% in 20-40 cm and 40-60 cm, respectively. Lower increases were for soil TN content (8-22% in 20-40 cm and 6-34% in 40-60 cm) than SOC content, which led to increase soil C:N ratio in the 20-60 cm soil depth. Compared with CK, remarkable increases of SOC and soil TN contents in 20-60 cm led to the decrease of stratification ratios (0-20: 20-60 cm), which promoted uniform distributions of SOC and TN in soil profiles. Even though soil parameters ranged widely according to the straw input, straw interlayer with 12 Mg ha^{-1} had higher SOC, TN, C:N ratio, and lower soil stratification ratio in 2015-2017, which contributed to salt leaching, water retention, and yield increment. These results highlighted the legacy effects of straw interlayers maintained more than four years, which led to an underestimation for previous short-term experiments, and demonstrated a great potential for subsoil fertility and salt-affected soil amelioration.

KEYWORDS

Straw interlayer; soil organic carbon; soil nitrogen; C:N ratio; saline soil.

1. INTRODUCTION

Globally, approximately 1.1×10^9 ha of lands are affected by soil salinity (Hopmans et al., 2021), which is threatening agricultural production, soil health, and food security (Sahab et al., 2020). China, for instance, has approximately 3.6×10^7 ha of saline soils, which possess great potential for agricultural utilization after amelioration (Rezapour et al., 2017; Yang et al., 2022). Saline soil plays a vital part in global carbon (C) and nitrogen (N) cycling, especially under the conditions of human intervention (Setia et al., 2013). Additionally, saline soil has low soil C and N contents, which intensify the negative effects of soil salinization (Huo et al., 2017).

Straw returning is widely recommended to maintain soil C and N contents through efficient use of the crop straw resource (Xia et al., 2018). Straw deep returning as an interlayer is an effective farming strategy for saline soil amelioration (Zhao et al., 2013a), which mitigates soil salinity (Zhao et al., 2013b), improves soil structure (Cong et al., 2019), regulates soil microbial community (Li et al., 2016), and boosts crop yield (Zhao et al., 2016). Soil C and N in farmland was mainly derived from crop straw, which affects soil C and N availability after mineralization (Lian et al., 2015). However, contradictory results were observed with different amounts of straw returning (Jin et al., 2020), due to local climatic conditions and soil properties (Hao et al., 2022). Excessive straw returning usually resulted in an undesirable soil C:N ratio (Zhang et al., 2015), prevented straw mineralization (Shahbaz et al., 2017a), and reduced crop production (Islam et al., 2022). However, insufficient straw amendment weakened soil C and N sequestration (Zhang et al., 2016), and did not meet the balance of soil C and N pools (Andruschkewitsch et al., 2013). Thus, it is critical to quantify the impacts of various amounts of straw deep returning as interlayers on soil C and N, especially in saline soils.

Inability to incorporate straw into deep soil constrain the C and N sequestrations (Zhao et al., 2018), while the legacy effects of straw deep returning on soil C and N remain unclear in saline soils (Zhai et al., 2021). The SOC content in 20-40 cm soil depth was increased in the first two years, while decreased from the third year under the condition of straw deep returning with 12 Mg ha^{-1} (Cong et al., 2019). However, this trend was influenced by the amount of straw input (Zhang et al., 2021), and it needed further investigation for saline soil (He et al., 2022). Meanwhile, soil C and N to straw deep returning varied widely at different soil depths (Dikgwatlhe et al., 2014). Straw deep returning (20-40 cm) increased SOC content by 8% in topsoil (0-20 cm), and up to 27% in the subsoil (20-40 cm) in the third year (Zheng et al., 2021). These resulted in different soil stratification ratios, a soil quality indicator of nutrient distribution in soil profile (Melero et al., 2012). Similar or opposite responses of soil TN content to straw returning were detected, compared to SOC content (Pittelkow et al., 2015), which led to varied soil C:N ratio. Thus, it is necessary to determine the impacts of straw deep returning as interlayer on SOC, TN, C:N ratio, and stratification ratio, considering the amount of straw input (Cong et al., 2019), experimental year (Berhane et al., 2020), and soil depth (Liu et al., 2021).

Therefore, we conducted a four-year field experiment with four levels of straw interlayers in the Hetao Irrigation District. We hypothesized that 1) the SOC increased in the first several years after straw deep returning, while decreased from subsequent years, it ranged according to the amount of straw input (Cong et al., 2019) and soil depth (Latifmanesh et al., 2020); and 2) straw deep returning led to similar trend between TN and SOC, which resulted in similar soil C:N ratio, while remarkable lower soil stratification ratios (Liu et al., 2021). Thus, we aimed to 1) quantify the effects of straw interlayers with different input rates on SOC and TN within 0-80 cm soil depth in four years after straw deep returning; 2) explore the relationships between straw interlayer and C:N ratio / stratification ratios, aiming to higher soil quality and productivity in a semi-arid saline soil.

2. MATERIALS AND METHODS

2.1. Study site

A field experiment was conducted in 2015-2018 at Yichang Irrigation station (41°07'N, 108deg00'E, 1 022 m ASL), in Wuyuan County, Inner Mongolia, China. This region has a semi-arid climate, with annual active accumulated temperature ([?] 10) of 3 100 degC. The average annual precipitation is ~200 mm, whereas potential evaporation is approximately 2 200 mm, indicating severe water deficit for crop production (Zhang et al., 2019). Precipitation mainly occurs in summer and autumn. Monthly precipitation and potential evaporation during the growing season (i.e., May-October) of the experimental years are shown in Figure 1. The soil is classified as chloride-sulfate saline soil with silty loam. Basic properties in 0-20 cm layer were as below: soil organic matter 11.3 g kg^{-1}, total nitrogen 0.6 g kg^{-1}, total phosphorus 0.7 g kg^{-1}, alkaline hydrolyzed nitrogen 57.3 mg kg^{-1}, available phosphorus 10.2 mg kg^{-1}, and available potassium 139 mg kg^{-1}. Soil nutrient contents in deeper soil layers (20-100 cm) are showed in Table 1. More information of the study site was descripted in Huo et al. (2017).

2.2. Experimental design

Four treatments were arranged as a completely randomized design with three replications: four straw interlayers with application rates of 0, 6, 12, and 18 Mg ha^{-1} (i.e., CK, SL6, SL12, and SL18) (Figure 2). The plot was 3.24 m^2 (1.8 m x 1.8 m) and separated by double-plastic sheets buried from soil surface to the soil depth of 100 cm to ensure no salt and water transports between adjacent plots. The interlayer material used in this study was chopped maize straw (C% = 42%, and N% = 0.65%). The straw was uniformly placed at 40 cm depth according to the amount required for each treatment in the first year, no additional straw input in subsequent years. The plots without straw interlayer (i.e., CK) were also ploughed to ensure similar soil disturbance. The plots used 180 kg N ha^{-1}, 53 kg P ha^{-1}, and 62 kg K ha^{-1} as base fertilizers, with forms of urea (N% = 46%), diammonium phosphate (N% = 18%, and P% = 20%), and potassium sulphate (K% = 41%). All plots were flood-irrigated as 185 mm from Yellow River (salt conc. 0.58 g L^{-1}) before sowing. All plots were mulched with plastic film with a width of 70 cm and a film spacing of 20 cm every year. The tested crop was sunflower (*Helianthus annuus* L.), which was seeded at a row spacing of 60 cm and a plant spacing of 20 cm on plastic film. The dates of sowing and harvest were shown in Table S1.

2.3. Soil sampling and measurements

Each year, soil samples were gathered in 0-20, 20-40, 40-60, and 60-80 cm layers between the two rows of sunflowers using a soil auger at sunflower harvest stage. The soil samples were naturally air-dried, sieved (0.149 mm) before SOC and TN determination. SOC content (g kg^{-1}) was measured by $K_2Cr_2O_7$-$FeSO_4$oxidation, and the TN content (g kg^{-1}) was analyzed by Kjeldahl method (Bao 2007). SOC and TN storages (Mg ha^{-1}) were determined as below:

$$SOC\ storage = \ SOC\ content \ \times \ BDi \ \times \ Hi \ \times \ 10(1)$$

$$TN\ storage = \ TN\ content \ \times \ BDi \ \times \ Hi \ \times \ 10(2)$$

Where BDi, Hi, and 10 represent the soil bulk density (g cm^{-3}), depth (m) and conversion factor, respectively.

The C:N ratio was determined by dividing the SOC content by the TN content. The stratification ratios of SOC and TN contents in 0-20 cm layer to that in the 20-60 cm and 60-80 cm soil layers were calculated as the method of Franzluebbers (2002). The methods of the measurements for soil moisture, soluble salt content, and crop yield were described in Zhang et al. (2020).

2.4. Statistical analysis

Data Processing System (DPS) was applied to perform statistical analyses. A three-way analysis of variance (ANOVA) together with Tukey's test was carried out to analyze the effects of experimental years (four levels: 2015, 2016, 2017 and 2018), soil depths (four levels: 0-20, 20-40, 40-60, and 60-80 cm), and straw interlayers (four levels: 0, 6, 12, and 18 Mg ha^{-1}) on SOC and TN contents, and soil C:N ratio. SOC content was significantly influenced by the interaction among these three factors. Therefore, a two-way ANOVA was performed to compare the effects of soil depths and straw interlayers on soil parameters in each year, and another two-way ANOVA was performed to examine the influences of experimental years and straw interlayers on soil parameters in each soil layer. When significant interactions were observed between experimental years / soil depths and straw interlayers, one-way ANOVA was conducted between straw interlayers in the same experimental year / soil depth. The Pearson's correlation coefficients between SOC / TN and soil salinity / crop yield were calculated using IBM SPSS Statistics 20.0 (SPSS Inc., ILZZ, USA). Figures were plotted with Origin 2020.

3. RESULTS

3.1. Soil Organic Carbon (SOC)

The relative changes of SOC content compared to CK were influenced by straw interlayers, and experimental year x straw interlayers interaction ($p< 0.05$) (Figure 3a). The relative changes of SOC content were decreased with the experimental years for SL6 and SL12, while it was increased with the experimental years for SL18. The highest SOC changes were found in 20-40 cm and 40-60 cm depths with 14-32% and 11-57%, respectively. In the first two years of straw interlayer burying, the relative change of SOC of each soil layer was the largest in SL12, but in later years SL18 showed an advantage. In 2018, the relative change of SOC under SL18 was the largest among all treatments.

The SOC content gradually decreased with deeper soil layers and increased in the straw interlayers ($p <$ 0.05) (Figure 4a). In 2015, the SOC content in SL12 with the greatest magnitude and increase by 19-57% (p < 0.05) compared with no straw interlayer. In 2016, the SOC content of straw interlayers was significantly increased by 24-31% and 32-35% ($p < 0.05$), respectively at the depths of 20-40 cm and 40-60 cm, compared with CK. Straw interlayer burial late stage (2017-2018), the SOC content of SL18 were higher than other treatments, and the largest increase was found in the depths of 20-40 cm and 40-60 cm.

Straw interlayers significantly affected SOC storage ($p< 0.05$) (Figure 5a). Compared with CK, SL6, SL12 and SL18 increased SOC storage by 8-22%, 14-34%, and 16-23% in 0-80 cm soil depth from 2015 to 2018, respectively. The SOC storage in SL12 with greatest magnitude among all straw treatments in 2015-2017.

3.2 Total Nitrogen (TN)

The relative changes of TN content compared to CK in 0-60 cm soil depth were significantly influenced by straw interlayers ($p < 0.01$), and experimental year xstraw interlayers interaction ($p< 0.01$) (Figure 3b). Straw interlayers (6-18 Mg ha^{-1}) increased TN content by 8-22% and 6-34% in 20-40 cm and 40-60 cm depth compared with CK. The relative changes of TN content were the largest under SL12 in the first three years of straw interlayer burial (2015-2017) but under SL18 in 2018.

Straw interlayers (SL6, SL12 and SL18) increased TN content (Figure 4b). In 2015, SL12 had the highest TN content, with an increase of 13 and 17% in 20-40 and 40-60 cm depths as compared to CK ($p< 0.05$), respectively. Similarly, in 2016, compared with CK, the TN content in SL6 and SL12 increased by 18 and 22% in 20-40 cm, and 23 and 15% in 40-60 cm ($p < 0.05$). In 2017, the changes of TN content relative to CK in SL12 and SL18 increased with the deepening soil layer, with the increase of 16-22% and 13-34%. In 2018, SL18 had the highest TN content compared with other treatments.

Straw interlayers significantly increased TN storage ($p< 0.05$) (Figure 5b). Compared with CK, straw interlayers increased TN storage by 6-17% in 2015-2018 ($p < 0.05$).

3.3. C:N ratio

The relative changes of C:N ratio compared to CK were higher in the early stage of straw interlayer burial (2015-2016), especially in 20-40 cm and 40-60 cm depths, which increased by 9-12% and 19-26%, respectively. Subsequently, the relative changes of C:N ratio between straw interlayer treatments fluctuated slightly (Figure 3c).

The C:N ratio increased at the beginning while subsequently decreased with increasing soil depth (Figure 4c). In 2015, compared with CK, SL6, SL12 and SL18 increased C:N ratio by 12, 17 and 9% in 20-40 cm soil depth, and 36, 34 and 16% in 40-60 cm depth, respectively ($p< 0.05$). In 2016, compared with CK, straw interlayers increased C:N ratio by 6-15% in 20-40 cm depth, SL12 and SL18 increased C:N ratio by 17 and 21% in 40-60 cm ($p < 0.05$). In 2017, straw interlayers (6-18 Mg ha^{-1}) boosted C:N ratio by 8-11% and 6-9% in 20-40 cm and 40-60 cm depth compared with CK, respectively. In 2018, C:N ratio increased with increasing amount of straw interlayer, but no significant difference with CK.

3.4. Stratification ratio s of SOC and TN

The stratification ratios of SOC and TN were influenced by straw interlayers ($p < 0.001$) and experimental year ($p< 0.01$) (Figure 6). Compared to CK, straw interlayers decreased the stratification ratios (0-20 cm: 20-60 cm) of SOC and TN by 5-15% (Fig. 6a) and 4-9% (Fig. 6b) ($p < 0.05$). In contrast, the stratification ratios of SOC and TN for 0-20 cm: 60-80 cm showed an opposite trend.

3.5. Relationships among SOC/TN and soil moisture, salinity, and sunflower yield

The SOC, TN and C:N ratio were positively correlated with soil moisture, but negatively correlated with soil salinity ($p < 0.01$). Sunflower yield significantly ($p < 0.01$) increased with increasing SOC and TN contents over four experimental years (Figure 7).

4. DISCUSSION

4.1. Effect of straw interlayer on SOC in saline soil

Straw interlayers significantly increased SOC contents in the present study, mainly due to exogenous organic material inputs with straw applications (Cong et al., 2019). Several studies demonstrated that straw returning to surface soils at rates greater than 9 Mg ha^{-1} could not increase SOC (Zhou et al., 2018), while straw deep returning as interlayers at rates of 12-18 Mg ha^{-1} increased SOC content in the third and fourth year after the treatments in this study. The contrasting results are probably because of the differing straw placement in these studies. Subsurface soil has lower microbial activity, decomposition and transformation rates than the surface soil (Latifmanesh et al., 2020), and can thus help retain C released from the straw. Our results confirm that straw interlayers have greater potential for SOC sequestration (Zou et al. 2016; Huo et al., 2017).

The SOC content of straw interlayer with 12 Mg $ha^{-1}$was highest in the first three years after straw deep returning. Overall, SOC content increased with straw C input when the added straw amount was smaller than the optimal value that allowed good straw and soil contact, but it was maintained or decreased when straw C input exceeded the optimal amount (Zhu et al., 2015). In the early period of burying a large amount of straw (i.e., 18 Mg ha^{-1} in this study), the straw was excessive and condensed in restricted soil space, it meant that the straw was in a reduced environment (Wang et al., 2015). This indicated that the straw interlayer was difficult to degrade and that its poor contact with the soil led to low decomposition rate and less SOC accumulation (Andruschkewitsch et al., 2013). Meanwhile, the C:N ratio in C-rich maize straw is generally higher than in the soil (Cai et al., 2015), and after the addition of 18 Mg straw ha^{-1}, microbial activities are restricted by the N availability in the early stage of straw decomposition (Laird and Chang 2013), which prompted microbial competition with crops for mineral N from the soil, affecting the composition and diversity of soil microorganisms, and thereby reducing straw decomposition rate (Yang et al., 2015). Whereas, SOC content significantly increased for the straw rates of 18 Mg ha^{-1} than 12 Mg ha^{-1}in the fourth year after straw deep returning. This is because that the limitation of soil space was weakened by the increase of straw burial years (Zhang et al., 2020).

Straw deep returning as interlayers increased SOC content and storage in soil layers above and below the straw interlayer. This is probably because the straw interlayers improved soil water-holding potential and reduced soil salt (Zhao et al., 2016), which promoted root growth and increased root C (Zhang et al., 2019) and inputs of exudates (Haichar et al., 2014). Meanwhile, the favorable soil porosity under straw interlayer promoted soluble organic C leaching to soil layer below straw interlayer (Huo et al., 2017). Additionally, the higher SOC content in 20-60 cm depth under straw interlayers resulted in lower stratification ratio (0-20 cm: 20-60 cm) compared with no straw interlayer. These data indicated that the straw interlayers were beneficial to solve the problem of nutrient accumulation caused by conventional straw (e.g., straw mulching or topsoil mixing) (Zou et al., 2016). This suggested that straw interlayer buried at 40 cm depth significantly increased SOC content and storage in 20-60 cm depth, and furthermore improved homogenous distribution of SOC content.

4.2. Effects of straw interlayer on TN and C:N ratio in saline soil

Our study also indicated that the straw interlayers increased the TN content and storage, especially in the soil near the straw interlayers, resulting in the decrease in stratification ratio of TN. It is mostly associated with the improvement of soil aggregate structure, and the decrease of soil bulk density after the straw interlayer placement (Zhang et al., 2015). Meanwhile, the C-rich straw stimulates microorganism growth in the process of decomposition and promotes their fixation of soil N (Cao et al., 2020). Additionally, straw returning can promote transformation of mineral N to organic N and reduce N loss via leaching (Yang et al., 2015). Thus, straw interlayer has positive effects on TN content and storage in soil layers near interlayer, further reducing the stratification ratio of TN content.

In our study, the straw interlayers increased C:N ratio in 20-60 cm depth. This may be explained by the nutrient composition of maize straw which has a C:N ratio of ˜65:1 (Cai et al., 2015). After being buried in soil, the contribution rate of straw interlayer to SOC is higher than that of TN (Liu et al., 2021). In addition, saline soils generally have lower C:N ratio, which may imply that mineralization and decomposition of SOC are reduced and SOC content is increased when large amounts of organic materials was added into soil (Tian et al., 2020). These can all contribute to increasing the soil C:N ratio.

Interestingly, we found that the improvement in soil C:N ratio declined with extension of straw interlayer burial time. As the time of straw burying developed, the difference in C:N ratio brought by different amounts of straw interlayer gradually weakened. In addition, as the burying period increases, the SOC gradually stabilized (Liu et al., 2014). However, straw returning with N fertilizer application enhanced N stabilization (Wang et al., 2021), which led to decrease of C:N ratio. Therefore, it indicated that soil C:N ratio increased at earlier period of straw interlayer burial and then stabilized.

4.3 Responses of SOC and TN to moisture and salinity in saline soil

The previous studies have showed that the straw interlayer can effectively increase water content, reduce salinity, and significantly increase crop yield (Zhao et al., 2016; Zhang et al., 2020). Furthermore, we found that SOC and TN contents were positively correlated with soil moisture and negatively with salt during 2015-2017 (p <0.01). In this study, the experimental plots were irrigated before planting sunflowers, and the straw interlayers could have extended the residential time of water in the upper part of straw interlayer and increased the water content in soil. Meanwhile, salt leaching was promoted to reduce the soil salt in root distribution layer (Zhao et al., 2016; Zhang et al., 2020). Additionally, the high-moisture and low-salt environment may be more conducive to the survival of soil microorganisms, thereby transforming the straw interlayer and increasing the SOC and TN contents (Li et al., 2017).

The SOC and TN contents had significantly negative correlation with soil salinity only in 2018 (p <0.01). With the increase of the straw interlayer burial period, the depth of the interlayer became thinner, and the regulation of water and salt weakened (Zhang et al., 2020). However, the salt content in 0-40 cm layer remained at a moderately level within the fourth year of straw interlayer burial. It may be beneficial to crop growth and residues induced-C transformation. Furthermore, the correlation analysis also confirmed that sunflower yield had a significant positive correlation with SOC and TN. Overall, straw interlayer with a single dose of 12 Mg ha^{-1} was recommended for improving SOC and TN during the first three years, it was beneficial for lowing soil salinity, while benefiting soil water content and crop yield in saline soil.

5. CONCLUSIONS

A 4-year field experiment demonstrated that straw interlayers (40 cm soil depth) increased SOC content by 16-24% compared to no straw interlayer (CK), ranged widely according to the straw input. Compared with CK, the increase of SOC content was decreased for straw interlayers with 6 and 12 Mg ha^{-1}, while it was increased for 18 Mg ha^{-1} with the experimental years. The SOC content of straw interlayer with 12 Mg ha^{-1} was highest in 2015-2017, while it was highest with 18 Mg ha^{-1} in 2018. The TN contents of straw interlayers were increased by 9-13% compared to CK, while the increment was lower than SOC content. Remarkable increases were obtained in the soil layers above (20-40 cm) and below (40-60 cm) the straw interlayers. Therefore, the C:N ratios of straw interlayers increased in 20-60 cm layers. Compared with CK, straw interlayers decreased the stratification ratios (0-20: 20-60 cm) of SOC and TN contents by 5-15% and 4-9%, respectively, which promoted a uniform distribution of SOC and TN contents in 0-60 cm soil layer. Overall, straw interlayer with 12 Mg ha^{-1} had higher SOC, TN, C:N ratio and lower soil stratification ratio in 2015-2017, which contributed to salts leaching, water retention, and yield increments. Our results highlighted the legacy effects of straw interlayers on soil fertility and productivity maintained more than four years associated with the amount of straw input, which led to the underestimation for previous short-term experiments. In conclusion, straw deep returning as interlayer was an effective strategy to increase the subsoil nutrients, reduce soil stratification ratio, and promote saline soil utilization.

Conflict of interest

We declare no competing interest.

Authors' contributions

Fangdi Chang: Investigation, Formal analysis, Data curation, Visualization, Writing - original draft. **Xi-**

quan Wang: Resources, Validation, Writing - review & editing. **Jiashen Song & Hongyuan Zhang & Ru Yu:** Investigation. **Jing Wang & Jian Liu:** Formal analysis. **Shang Wang & Hongjie Ji** : Writing-review & editing. **Yuyi Li (the corresponding author):** Project organization, Conceptualization, Strategy, Writing - review & editing.

REFERENCE

Andruschkewitsch, R., Geisseler, D., Koch, H. J., & Ludwig, B. (2013). Effects of tillage on contents of organic carbon, nitrogen, water-stable aggregates and light fraction for four different long-term trials. *Geoderma* , *192* , 368-377. https://doi.org/10.1016/j.geoderma.2012.07.005

Bao, S. D. (2007). Soil and agricultural chemistry analysis (3rd ed.). Beijing: China Agriculture Press, pp.30-34 (In Chinese).

Berhane, M., Xu, M., Liang, Z. Y., Shi, J. L., Wei, G. H., & Tian, X. H. (2020). Effects of long-term straw return on soil organic carbon storage and sequestration rate in North China upland crops: A meta-analysis. *Global Change Biology* , *26* , 2686-2701. https://doi.org/10.1111/gcb.15018

Cai, M., Dong, Y. J., Chen, Z. J., Kalbitz, K., & Zhou, J. B. (2015). Effects of nitrogen fertilizer on the composition of maize roots and their decomposition at different soil depths. *European Journal of Soil Biology* , *67* , 43-50. https://doi.org/10.1016/j.ejsobi.2015.02.001

Cong, P., Li, Y. Y., Wang, J., Gao, Z. J., Pang, H. C., Zhang, L., Liu, N., & Dong, J. X. (2019). Increasing straw incorporation rates improves subsoil fertility and crop yield in the Huang-Huai-Hai Plain of China.*Archives of Agronomy and Soil Science* , *66* (14), 1-15. https://doi.org/10.1080/03650340.2019.1704735

Dikgwatlhe, S.B., Chen, Z. D., Lal, R., Zhang, H. L., & Chen, F. (2014). Changes in soil organic carbon and nitrogen as affected by tillage and residue management under wheat-maize cropping system in the North China Plain. *Soil and Tillage Research* , *144* , 110-118. https://doi.org/10.1016/j.still.2014.07.014

Franzluebbers, A. J. (2002). Soil organic matter stratification ratio as an indicator of soil quality. *Soil and Tillage Research* ,*66* , 95-106. https://doi.org/10.1016/s0167-1987(02)00018-1

Gao, L., Li, W., Ashraf, U., Lu, W.J., Li, Y. L., Li, C. Y., Li, G. Y., Li, G. K., & Hu, J. G. (2020). Nitrogen fertilizer management and maize straw return modulate yield and nitrogen balance in sweet corn.*Agronomy* , *10* (3), 362. https://doi.org/10.3390/agronomy10030362

Haichar, F. E. Z., Santaella, C., Heulin, T., & Achouak, W. (2014). Root exudates mediated interactions belowground. *Soil Biology and Biochemistry* , *77* , 69-80. https://doi.org/10.1016/j.soilbio.2014.06.017

Hao, X. X., Han, X. Z., Wang, S. Y., & Li, L. J. (2022). Dynamics and composition of soil organic carbon in response to 15 years of straw return in a Mollisol. *Soil and Tillage Research* , *215* , 105221. https://doi.org/10.1016/j.still.2021.105221

He, W., Wang, H., Ye, W. H., Tian. Y. L., Hu, G. Q., Lou, Y. H., Pan, H., Yang, Q. G., & Zhuge, Y. P. (2022). Distinct stabilization characteristics of organic carbon in coastal salt-affected soils with different salinity under straw return management. *Land Degradation & Development* , *2022* , 1-12. https://doi.org/10.1002/ldr.4276

Hopmans, J. W., Qureshi, A.S., Kisekka, I., Munns, R., Grattan, S. R., Rengasamy, P., Ben-Gal, A., Assouline, S., Javaux, M., Minhas, P. S., Raats, P. A. C., Skaggs, T. H., Wang, G, De Jong van Lier, Q., Jiao, H., Lavado, R. S., Lazarovitch, N., Li, B., & Taleisnik, E. (2021). Critical knowledge gaps and research priorities in global soil salinity.*Advances in Agronomy* , *169* , 1-191. https://doi.org/10.1016/bs.agron.2021.03.001

Huo, L., Pang, H. C., Zhao, Y. G., Wang, J., Lu, C., & Li, Y. Y. (2017). Buried straw layer plus plastic mulching improves soil organic carbon fractions in an arid saline soil from northwest China. *Soil and Tillage Research* , *165* , 286-293. https://doi.org/10.1016/j.still.2016.09.006

Islam, M. U., Guo, Z. C., Jiang, F. H., & Peng, X. H. (2022). Does straw return increase crop yield in the wheat-maize cropping system in China? A meta-analysis. *Field Crops Research* , *279* , 108447. https://doi.org/10.1016/j.fcr.2022.108447

Jin, Z. Q., Shah, T., Zhang, L., Liu, H. Y., Peng, S. B., & Nie, L. X. (2020). Effect of straw returning on soil organic carbon in rice-wheat rotation system: A review. *Food and Energy Security* , *9* , e200. https://doi.org/10.1002/fes3.200

Laird, D. A., & Chang, C.W. (2013). Long-term impacts of residue harvesting on soil quality. *Soil and Tillage Research* ,*134* , 33-40. http://doi.org/10.1016/j.still.2013.07.001

Latifmanesh, H., Deng, A. X., Li, L., Chen, Z. J., Zheng, Y. T., Bao, X. T., Zheng, C. Y., & Zhang, W. J. (2020). How incorporation depth of corn straw affects straw decomposition rate and C&N release in the wheat-corn cropping system. *Agriculture, Ecosystems & Environment* , *300* , 107000. https://doi:10.1016/j.agee.2020.107000

Li, S., Chen, J., Shi, J. L., Tian, X. H., Li, X. S., Li, Y. B., & Zhao, H. L. (2017). Impact of straw return on soil carbon indices, enzyme activity, and grain production. *Soil Science Society of America Journal* , *81* , 1475-1485. https://doi.org/10.2136/sssaj2016.11.0368

Li, Y. Y., Pang, H. C., Han, X. F., Yan, S. W., Zhao, Y. G., Wang, J., Zhai, Z., & Zhang, J. L. (2016). Buried straw layer and plastic mulching increase microflora diversity in salinized soil. *Journal of Integrative Agriculture* , *15* (7), 1602-1611. https://doi.org/10.1016/s2095-3119(15)61242-4

Lian,T. X., Wang, G. H., Yu, Z. H., Li, Y. S., Liu, Y. B., & Jin, J. (2015). Carbon input from ^{13}C- labelled soybean residues in particulate organic carbon fractions in a Mollison.*Biology and Fertility of Soils* , *52* , 331-339. https://doi.org/10.1007/s00374-015-1080-6

Liu, C., Lu, M., Cui, J., Li, B., & Fang, C. M. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: A meta-analysis. *Global Change Biology* , *20* , 1366-1381. https://doi.org/10.1111/gcb.12517

Liu, N., Li, Y. Y., Cong, P., Wang, J., Guo, W., Pang, H. C., & Zhang, L. (2021). Depth of straw incorporation significantly alters crop yield, soil organic carbon and total nitrogen in the North China Plain.*Soil and Tillage Research* , *205* , 104772. https://doi.org/10.1016/j.still.2020.104772.

Melero, S., Lopez-Bellido, R. J., Lopez-Bellido, L., Munoz-Romero, V., Moreno, F., Murillo, J. M., Franzluebbers, A. J. (2012). Stratification ratios in a rainfed Mediterranean Vertisol in wheat under different tillage: rotation and N fertilisation rates. *Soil and Tillage Research* , *119* , 7-12. https://doi.org/10.1016/j.still.2011.11.012.

Pittelkow, C. M., Liang, X. Q., Linquist, B. A., Groenigen, K. J., Lee, J., Lundy, M. E., Gestel, N., Six, J., Venterea, R. T., & Kessel, C. (2014). Productivity limits and potentials of the principles of conservation agriculture. *Nature* , *517* , 365-368. https://doi.org/10.1038/nature13809

Rezapour, S., Kalashypour, E., & Asadzadeh, F. (2017). Assessment of the quality of salt-affected soils after irrigation and cultivation in semi-arid condition. I*nternational Journal of Environmental Research* , *11* , 301-313. https://doi.org/10.1007/s41742-017-0028-0

Sahab, S., Suhani, I., Srivastava, V., Chauhan, P. S., Singh, R. P., & Prasad, V. (2020). Potential risk assessment of soil salinity to agroecosystem sustainability: current status and management strategies.*Science of the Total Environment* , *764* , 144164. https://doi.org/10.1016/j.scitotenv.2020.144164

Setia, R., Smith, P., Marschner, P., Baldock, J., Chittleborough, D., & Smith, J. (2011). Introducing a decomposition rate modifier in the rothamsted carbon model to predict soil organic carbon stocks in saline soils. *Environmental Science & Technology* , *45* (15), 6396-6403. https://doi.org/10.1021/es200515d

Shahbaz, M., Kuzyakov, Y., & Heitkamp, F. (2017a). Decrease of soil organic matter stabilization with increasing inputs: mechanisms and controls. *Geoderma* , *304* , 76-82. https://doi.org/10.1016/j.geoderma.2016.05.019a

Tian, P., Lian, H. L., Wang, Z. Y., Jiang, Y., Li, C. F., Sui, P. X., & Qi, H. (2020). Effects of deep and shallow tillage with straw incorporation on soil organic carbon, total nitrogen and enzyme activities in northeast China. *Sustainability* , *12* , 8679. https://doi.org/10.3390/su12208679

Wang, F. W., Wang, X. B., Li, J. C., Ye, A. H., & Wang, Y. (2015). Effects of fertilization and straw incorporation on bacterial communities in lime concretion black soil. *Chinese Journal of Eco-Agriculture* , *23* (10), 1302-1311. https://doi.org/10.13930/j.cnki.cjea.150267 (In Chinese)

Wang, S. C., Lu, C. A., Huai, S. C., Yan, Z. H., Wang, J. Y., Sun, J. Y., & Raza, S. (2021). Straw burial depth and manure application affect the straw-C and N sequestration: Evidence from ^{13}C and^{15}N-tracing. *Soil and Tillage Research* ,*208* , 104884. https://doi.org/10.1016/j.still.2020.104884

Xia, L. L., Lam, S. K., Wolf, B., Kiese, R., Chen, D. L., & Butterbach-Bahl, K. (2018). Trade-offs between soil carbon sequestration and reactive nitrogen losses under straw return in global agroecosystems. *Global Change Biology* , *24* , 5919-5932. http://doi.org/10.1111/gcb.14466

Yang, H. S, Yang, B., Dai, Y. J., Xu, M. M., Koide, R. T., Wang, X. H., Liu, J., & Bian, X. M. (2015). Soil nitrogen retention is increased by ditch-buried straw return in a rice-wheat rotation system.*European Journal of Agronomy* , *69* , 52-58. http://doi.org/10.1016/j.eja.2015.05.005

Yang, J. S., Yao, R. J., Wang, X. P., Xie, W. P., Zhang, X., Zhu, W., Zhang, L., Sun, R. J. (2022). Research on salt-affected soils in China: history, status quo and prospect. *Acta Pedologica Sinica* ,*59* (1), 10-27. https://doi.org/10.11766/trxb202110270578 (In Chinese)

Zhai, S. L., Xu, C. F., Wu, Y. C., Liu, J., Meng, Y. L., & Yang, H. S. (2021) Long-term ditch-buried straw return alters soil carbon sequestration, nitrogen availability and grain production in a rice-wheat rotation system. *Crop & Pasture Science* ,*72* (4), 245-254. https://doi.org/10.1071/CP20444

Zhang, H. Y., Hobbie, E. A., Feng, P. Y., Zhou, Z. X., Niu, L. A., Duan, W. K., Hao, J. M., & Hu, K. L. (2021). Responses of soil organic carbon and crop yields to 33-year mineral fertilizer and straw additions under different tillage systems. *Soil and Tillage Research* , *209* , 104943. https://doi.org/10.1016/j.still.2021.104943

Zhang, H. Y., Pang, H. C., Lu, C., Zhang, X., & Li, Y. Y. (2019). Subsurface organic amendment plus plastic mulching promotes salt leaching and yield of sunflower. *Agronomy Journal* , *111* , 457-466. https://doi.org/10.2134/agronj2018.02.0097

Zhang, H. Y., Pang, H. C., Zhao, Y. G., Lu, C., Liu, N., Zhang, X. L., & Li, Y. Y. (2020). Water and salt exchange flux and mechanism in a dry saline soil amended with buried straw of varying thicknesses.*Geoderma* , *365* , 114213. https://doi.org/10.1016/j.geoderma.2020.114213

Zhang, P., Chen, X. L., Wei, T., Yang, Z., Jia, Z. K., Yang, B. P., Han, Q. F., & Ren, X. L. (2016). Effects of straw incorporation on the soil nutrient contents, enzyme activities, and crop yield in a semiarid region of China. *Soil and Tillage Research* . *160* , 65-72. https://doi.org/10.1016/j.still.2016.02.006

Zhang, P., Wei, T., Li, Y. L., Wang, K., Jia, Z. K., Han, Q. F., & Ren, X. L. (2015). Effects of straw incorporation on the stratification of the soil organic C, total N and C:N ratio in a semiarid region of China.*Soil and Tillage Research* .*153* , 28-35. https://doi.org/10.1016/j.still.2015.04.008

Zhao, Y. C., Wang, M. Y., Hu, S. J., Zhang, X. D., Ouyang, Z., Zhang, G. L., Biao, H., Zhao, S. W., Wu, J. S., Xie, D. T., Zhu, B., Yu, D. S., Pan, X. Z., Xu, S. X., & Shi, X. Z. (2018). Economics- and policy-driven organic carbon input enhancement dominates soil organic carbon accumulation in Chinese croplands. *Proceedings of the National Academy of Sciences of the United States of America* ,*115* (16), 4045-4050. https://doi.org/10.1073/pnas.1700292114

Zhao, Y. G., Li, Y. Y., Hu, X. L., Wang, J., & Pang, H. C. (2013b). Effects of plastic mulching and deep burial of straw on dynamics of soil water and salt in micro-plot field cultivation. *Acta Pedologica Sinica* , *50* , 1129-1137. https://doi.org/10.11766/trxb201212300536 (In Chinese)

Zhao, Y. G., Li, Y. Y., Wang, J., Pang, H. C., & Li, Y. Y. (2016). Buried straw layer and plus plastic mulching reduces soil salinity and increases sunflower yield in saline soils. *Soil and Tillage Research* , *155* , 363-370. https://doi.org/10.1016/j.still.2015.08.019

Zhao, Y. G., Wang, J., Li, Y. Y., & Pang, H. C. (2013a). Reducing evaporation from phreatic water and soil resalinization by using straw interlayer and plastic mulch. *Transactions of the Chinese Society of Agricultural Engineering* , *29* , 109-117. https://doi.org/10.3969/j.issn.1002-6819.2013.23.015 (In Chinese)

Zheng, S., Dou, S., Duan, H. M., Zhang, B. Y., & Bai, Y. (2021). Fluorescence spectroscopy and ^{13}C NMR spectroscopy characteristics of HA in black soil at different corn straw returning modes. *International Journal of Analytical Chemistry* , *6* , 1-9. https://doi.org/10.1155/2021/9940116

Zhou, D. X., Su, Y., Ning, Y. C., Rong, G. H., Wang, G. D., Liu, D., & Liu, L. Y. (2018). Estimation of the effects of maize straw return on soil carbon and nutrients using response surface methodology.*Pedosphere* , *28* (3), 411-421. https://doi.org/10.1016/s1002-0160(18)60024-4

Zhu, L. Q., Hu, N. J., Zhang, Z. W., Xu, J. L., Tao, B. R., & Meng, Y. L. (2015). Short-term responses of soil organic carbon and carbon pool management index to different annual straw return rates in a rice-wheat cropping system. *Catena* ,*135* , 283-289. http://doi.org/10.1016/j.catena.2015.08.008

Zou, H. T., Ye, X. H., Li, J. Q., Lu, J., Fan, Q. F., Yu, N., Zhang, Y. L., Dang, X. L., & Zhang, Y. L. (2016). Effects of straw return in deep soils with urea addition on the soil organic carbon fractions in a semi-arid temperate cornfield. *Plos one* , *11* , e0153214. https://doi.org/10.1371/journal.pone.0153214

TABLE 1 Background nutrient in 0-100 cm of the experimental soil measured before starting the field experiment (May 2015).

Soil depth (cm)	Organic matter (g kg^{-1})	Total nitrogen (g kg^{-1})	Total phosphorus (g kg^{-1})	Alkaline hydrolysis N (m
0-20	11.33	0.59	0.68	57.3
20-40	9.67	0.57	0.63	45.3
40-60	8.95	0.48	0.56	30.7
60-80	7.74	0.41	0.52	29.0
80-100	7.45	0.39	0.50	26.7

Figure captions

FIGURE 1 Monthly rainfall and evaporation in the growing period (2015-2018).

FIGURE 2 Field planting and management showing straw interlayer burial, irrigation and sowing.

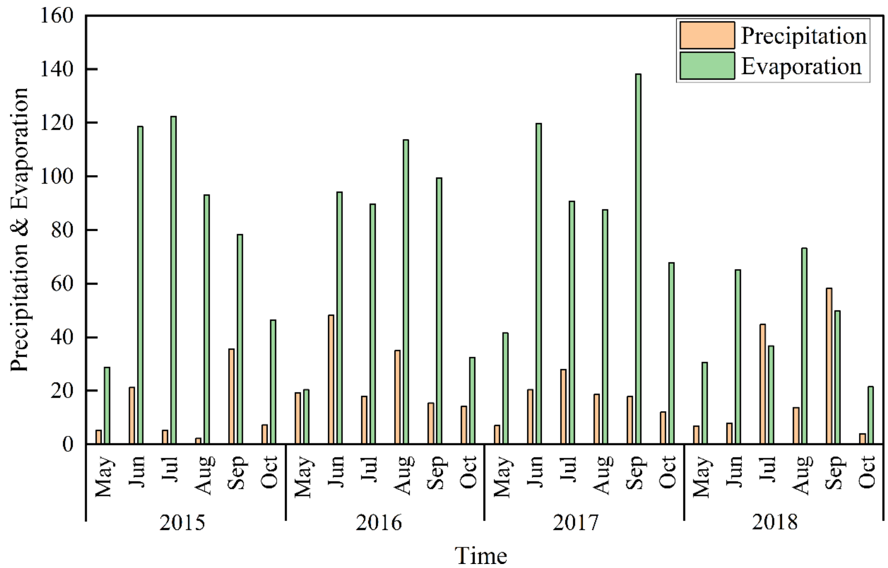
FIGURE 3 Changes of SOC (a), TN (b) and C:N ratio (c) in straw interlayers relative to the CK for different soil depths during 2015-2018. The changes (%) were calculated as (Value in Treatment – Value in CK) / Value in CK × 100. CK: no straw interlayer; SL6: 6 Mg straw ha^{-1} as an interlayer; SL12: 12 Mg straw ha^{-1} as an interlayer; SL18: 18 Mg straw ha^{-1} as an interlayer. Values are mean (± SE).

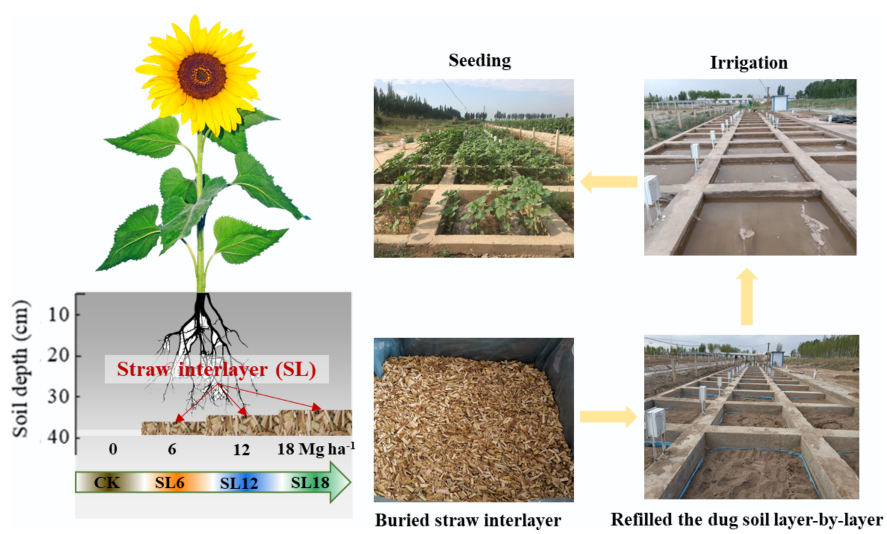
FIGURE 4 Contents of soil organic carbon (SOC) (a) and total nitrogen (TN) (b), and C:N ratio (c) in the soil profile under straw interlayers in 2015-2018. CK: no straw interlayer; SL6: 6 Mg straw ha^{-1} as an interlayer; SL12: 12 Mg straw ha^{-1} as an interlayer; SL18: 18 Mg straw ha^{-1} as an interlayer. Values are mean (± SE).

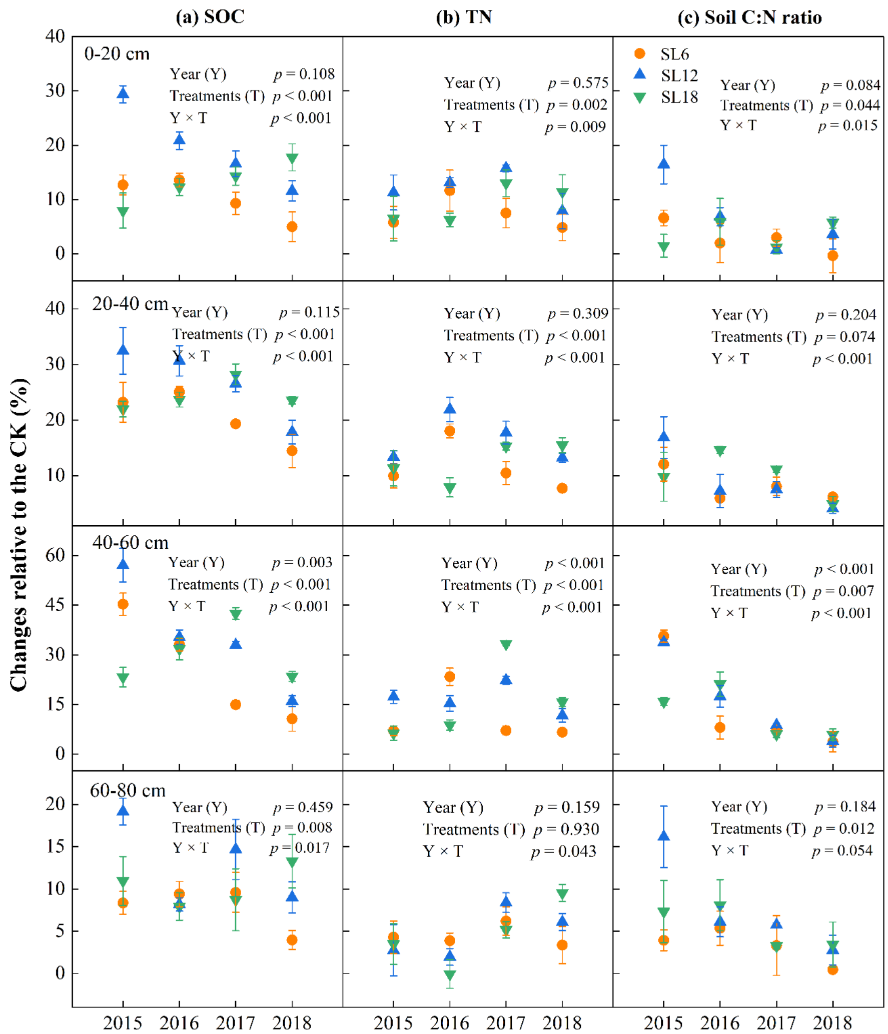
FIGURE 5 Storages of soil organic carbon (SOC) (a) and total nitrogen (TN) (b) under straw interlayers in 2015-2018. CK: no straw interlayer; SL6: 6 Mg straw ha^{-1} as an interlayer; SL12: 12 Mg straw ha^{-1} as an interlayer; SL18: 18 Mg straw ha^{-1} as an interlayer. Different small letters show a significantly difference ($p < 0.05$) between straw interlayers in each year. Values are mean (± SE).

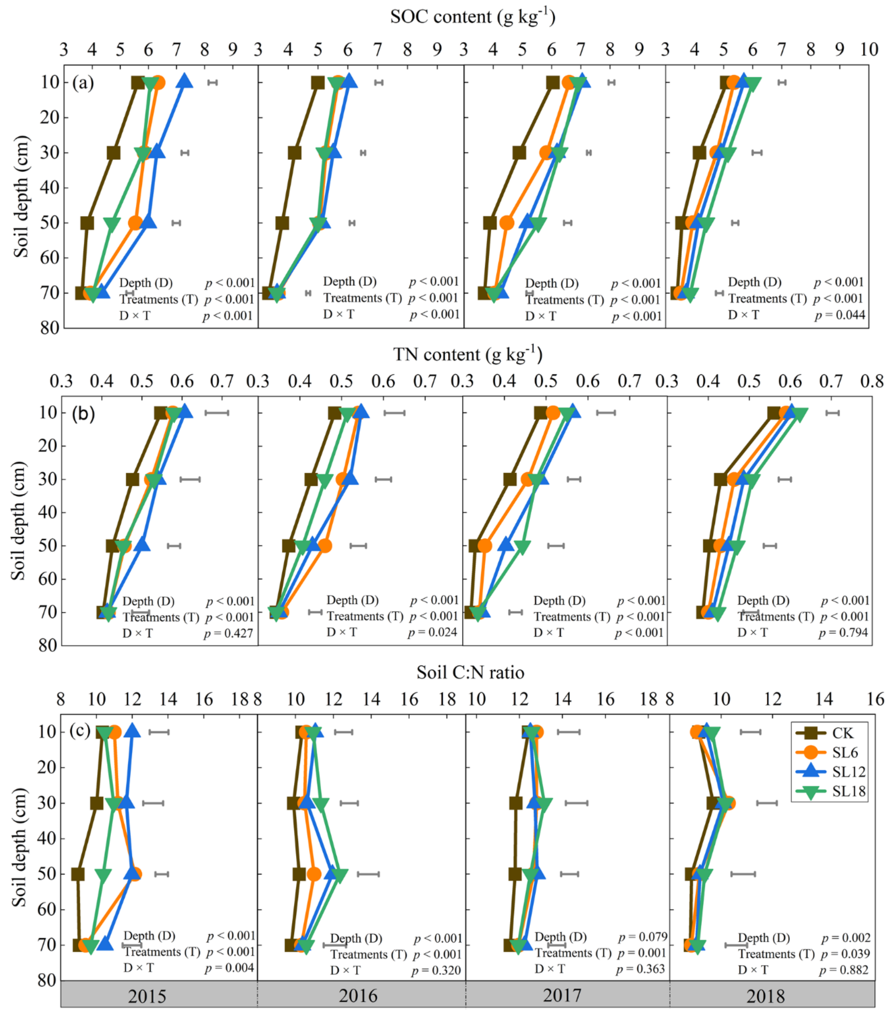
FIGURE 6 Stratification ratio of soil organic carbon (SOC) (a) and soil total nitrogen (TN) (b) under straw interlayers.CK: no straw interlayer; SL6: 6 Mg straw ha^{-1} as an interlayer; SL12: 12 Mg straw ha^{-1} as an interlayer; SL18: 18 Mg straw ha^{-1} as an interlayer. Different small letters show a significantly difference ($p < 0.05$) between interlayers in each year. Values are mean (± SE).

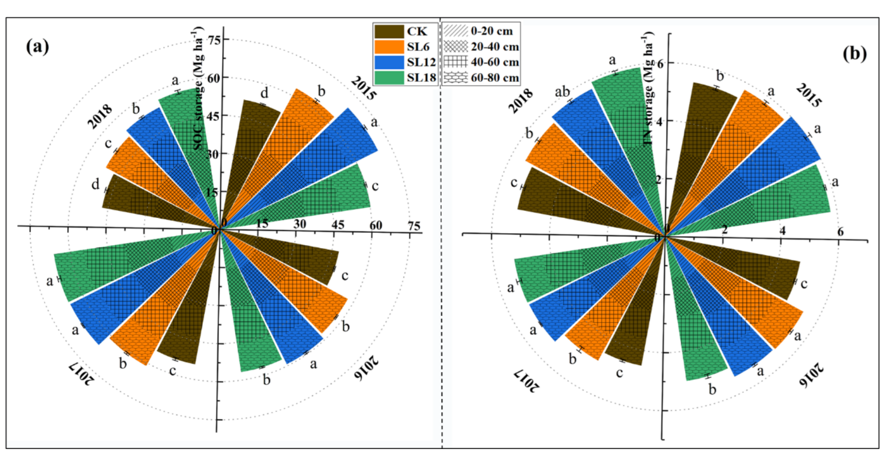
FIGURE 7 Correlations of soil organic carbon (SOC), total nitrogen (TN), C:N ratio, stratification ratios with soil moisture, soil salinity and crop yield from 2015 to 2018.

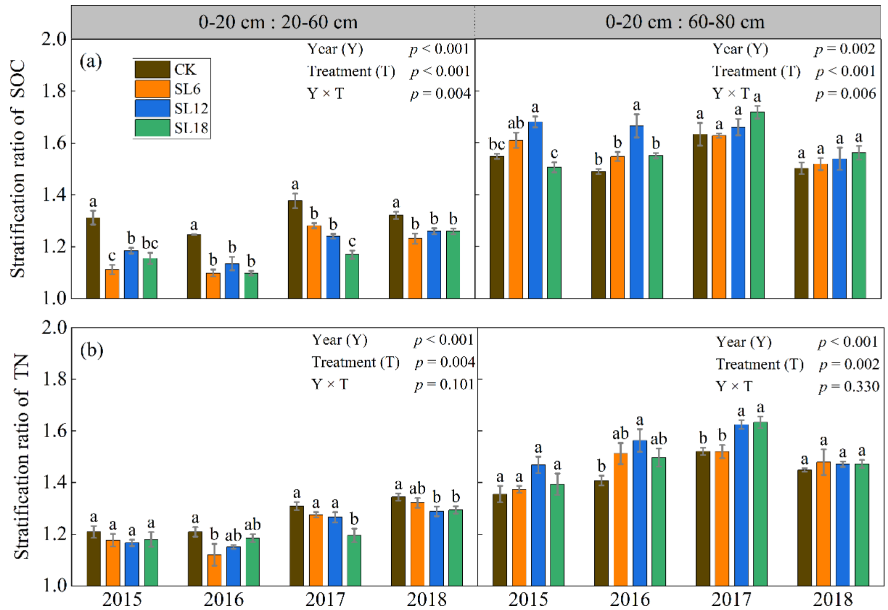




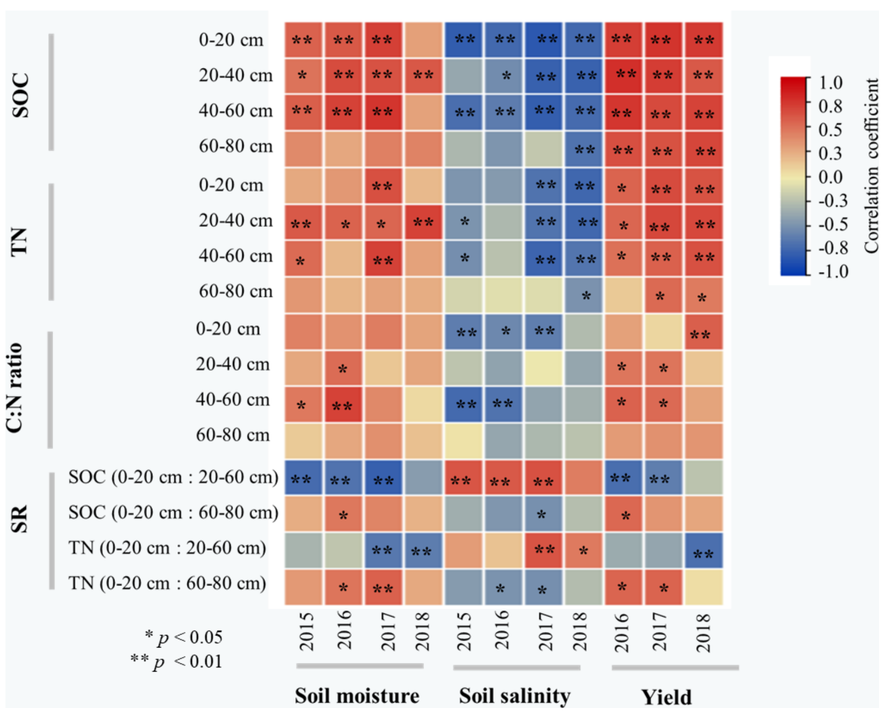

(a) SOC
(b) TN
(c) Soil C:N ratio
SL6
SL12
SL18
Changes relative to the CK (%)
0-20 cm
Year (Y) p = 0.108
Treatments (T) p < 0.001
Y × T p < 0.001
Year (Y) p = 0.575
Treatments (T) p = 0.002
Y × T p = 0.009
Year (Y) p = 0.084
Treatments (T) p = 0.044
Y × T p = 0.015
20-40 cm
Year (Y) p = 0.115
Treatments (T) p < 0.001
Y × T p < 0.001
Year (Y) p = 0.309
Treatments (T) p < 0.001
Y × T p < 0.001
Year (Y) p = 0.204
Treatments (T) p = 0.074
Y × T p < 0.001
40-60 cm
Year (Y) p = 0.003
Treatments (T) p < 0.001
Y × T p < 0.001
Year (Y) p < 0.001
Treatments (T) p < 0.001
Y × T p < 0.001
Year (Y) p < 0.001
Treatments (T) p = 0.007
Y × T p < 0.001
60-80 cm
Year (Y) p = 0.459
Treatments (T) p = 0.008
Y × T p = 0.017
Year (Y) p = 0.159
Treatments (T) p = 0.930
Y × T p = 0.043
Year (Y) p = 0.184
Treatments (T) p = 0.012
Y × T p = 0.054
2015
2016
2017
2018


SOC content (g kg-1)
TN content (g kg-1)
Soil C:N ratio
Soil depth (cm)
(a)
(b)
(c)
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p < 0.001
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p < 0.001
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p < 0.001
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.044
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.427
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.024
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p < 0.001
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.794
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.004
Depth (D) p < 0.001
Treatments (T) p < 0.001
D × T p = 0.320
Depth (D) p = 0.079
Treatments (T) p = 0.001
D × T p = 0.363
Depth (D) p = 0.002
Treatments (T) p = 0.039
D × T p = 0.882
CK
SL6
SL12
SL18
2015
2016
2017
2018


(a)
(b)
SOC storage (Mg ha-1)
TN storage (Mg ha-1)
CK
SL6
SL12
SL18
0-20 cm
20-40 cm
40-60 cm
60-80 cm
2015
2016
2017
2018



0-20 cm : 20-60 cm
0-20 cm : 60-80 cm
(a)
CK
SL6
SL12
SL18
Year (Y) p < 0.001
Treatment (T) p < 0.001
Y × T p = 0.004
Year (Y) p = 0.002
Treatment (T) p < 0.001
Y × T p = 0.006
Stratification ratio of SOC
(b)
Year (Y) p < 0.001
Treatment (T) p = 0.004
Y × T p = 0.101
Year (Y) p < 0.001
Treatment (T) p = 0.002
Y × T p = 0.330
Stratification ratio of TN
2015
2016
2017
2018



SOC
TN
C:N ratio
SR
0-20 cm
20-40 cm
40-60 cm
60-80 cm
SOC (0-20 cm : 20-60 cm)
SOC (0-20 cm : 60-80 cm)
TN (0-20 cm : 20-60 cm)
TN (0-20 cm : 60-80 cm)
Soil moisture
Soil salinity
Yield
* p < 0.05
** p < 0.01
Correlation coefficient