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RESEARCH ARTICLE

Effects of plantation age and precipitation gradient on soil carbon and nitrogen changes following afforestation in the Chinese Loess Plateau

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Abstract

Afforestation of degraded land significantly influences soil organic carbon (SOC) and total nitrogen (STN) sequestration. The interaction effects of plantation age and climate gradient on SOC and STN changes following afforestation are not well understood. In this study, five sites were selected along a precipitation gradient (410–600 mm yr^{-1}) in the Loess Plateau. The SOC and STN stocks at a depth of 0–200 cm were measured in cropland and black locust (*Robinia pseudoacacia* L.) forests with different plantation ages, that is, young forest (<15 years), middle-aged forest (15–25 years), and old forest (>25 years). The SOC and STN stocks in the 0- to 200-cm profiles of young forest, middle-aged forest, and cropland increased significantly with mean annual precipitation ($p < .05$), whereas the increasing trend of the SOC stocks of old forest was not significant, indicating an age-dependent change in the SOC and STN stocks across the precipitation gradient. The SOC stock change (SOC) following afforestation increased with mean annual precipitation in young forest, but it had a decreasing trend in middle-aged and old forests. The STN stock changes (STN) in the three forests were negative at most sites, and they all decreased along the precipitation gradient. There were significant positive correlations between SOC and STN ($p < .01$), and 1-g STN stock accumulation was accompanied by 8.40-, 6.10-, and 10.48-g SOC accumulation for young forest, middle-aged forest, and old forest, respectively. The different patterns of SOC and STN stock changes should be incorporated into soil C and N modelling and estimation.

KEYWORDS
afforestation, Loess Plateau, plantation age, precipitation gradient, soil C and N stocks

1 | INTRODUCTION

Land degradation has long been a severe environmental issue in arid and semiarid regions of the world (Jamal, Javed, & Khanday, 2016; Kędra & Szczepanek, 2019). Human-aided afforestation of degraded or cultivated land is an effective measure to control soil erosion, increase soil carbon sequestration, and recover ecosystems (Deng, Liu, & Shangguan, 2014; García-Díaz et al., 2016). Forest expansions usually result in higher plant biomass and more litter input, which accelerated vegetation restoration, reduced soil degradation, and increased soil carbon (C) and nitrogen (N) sequestration (Laganière, Angers, & Paré, 2010; Yang, Luo, & Finzi, 2011; Zhong et al., 2019).

Soil organic carbon (SOC) accumulation depends largely on plant net primary productivity (NPP; Jobbágy & Jackson, 2000; Liu et al., 2018), which is mainly limited by N fixation in most terrestrial ecosystems (Averill & Waring, 2018; Luo et al., 2004; Vitousek & Howarth, 1991). The C–N interaction is an important indicator of carbon sequestration sustainability following afforestation; thus, this topic has attracted considerable attention in recent years (Chang, Jin, Lü, Liu, & Fu, 2014; Deng & Shangguan, 2017; Durán et al., 2017). Elucidating the SOC and soil total nitrogen (STN) dynamics and investigating their interactions during the afforestation process can provide important information for predicting regional C and N cycles and ensuring the sustainable management of land resources (Liu et al., 2018).

The effects of afforestation on soil C and N depend on plantation age, species, climatic, and topographic, and edaphic factors, and the regulating processes are variable at different scales (Chang, Fu, Liu, Wang, & Yao, 2012; Deng, Wang, Liu, & Shangguan, 2016; Jia, Shao, & Wei, 2012; Jobbágy & Jackson, 2000). An increasing number of studies have indicated that the plantation age of afforestation is a critical factor in soil C and N sequestration. Paul, Polglase, Nyakuengama, and Khanna (2002) analysed the global data on soil C changes following afforestation and found that surface soil C (<10 cm) decreased by 3.46% per year during the first 5 years, whereas it increased by 0.50–0.86% in stands older than 30 years. Li, Niu, and Luo (2012) found significant increases in soil C and N stocks after 30 and 50 years of afforestation, but they were either depleted or unchanged before these time points. Chen et al. (2013) reported a decrease in soil C in Chinese fir plantations 16 years after planting, whereas soil C started accumulating between 16 and 21 years after afforestation and subsequently became stable. In contrast to the results described above, Chen, Gao, Pang, Chen, and Ye (2018) found consistent increases in SOC and STN contents in the 0- to 100-cm profile with plantation age in restored mangrove forests (*Kandelia obovata*) in South China. Li et al. (2019) also showed that SOC and STN stocks significantly increased as Caragana intermedia plantation age increased in an alpine sandy land. Therefore, the effects of plantation age on soil C and N dynamics after afforestation are complex and are influenced by vegetation type, restoration time, and climate factors (Deng & Shangguan, 2017).

Precipitation plays important roles in affecting soil C and N changes after afforestation. The increases in precipitation result in high NPP, which leads to high soil C and N accumulation (Aranibar et al., 2004; Chang et al., 2014; Wang, Li, Ye, Chu, & Wang, 2010). Aranibar et al. (2004) indicated a strong effect of mean annual precipitation (MAP) variability on N cycling in leguminous plants, that is, SOC and C/N decreased with aridity. Raheb, Heidari, and Mahmoodi (2017) indicated that the SOC stock in the 0- to 120-cm profile increased with MAP in northwestern Iran. However, Berthrong, Piñeiro, Jobbágy, and Jackson (2012) found that SOC and STN increased in drier sites, whereas they decreased in wetter sites after afforestation across a 600- to 1,500-mm rainfall gradient in Argentina and Uruguay, and the magnitudes of SOC and STN gains or losses were larger in older plantations. The above studies showed inconsistent trends in soil C and N with increasing precipitation and indicated that both plantation age and precipitation conditions were critical factors affecting soil C and N changes (Li et al., 2019; Peltoniemi, Mäkipää, Liski, & Tamminen, 2004). Further investigations are needed to detect the interaction influences of plantation age and precipitation gradient on soil C and N changes following afforestation.

The “Grain for Green” program was implemented in the Loess Plateau of China in 1999 for the restoration of degraded ecosystems (Cao, Chen, & Yu, 2009). In this large-scale ecological restoration project, there were significant conversions of sloping farmland to woodland and grassland, which enhanced soil conservation, carbon sequestration (Lü et al., 2012), and soil-water carrying capacity of vegetation (Jia, Shao, Yu, Zhang, & Binley, 2019). Many studies have investigated soil C and N changes following afforestation at the catchment or regional scale. Zhang, Zhang, and Cao (2018) found that soil C and N storage decreased in the early stages of afforestation (9 and 17 years, respectively) for black locust (*Robinia pseudoacacia* L.) plantations in the Zhifanggou catchment. Jia, Yang, Zhang, Shao, and Huang (2017) detected a general decrease in the SOC in three vegetation types (forestland, grassland, and cropland) along the precipitation gradient of 620–400 mm from the south to north of the Loess Plateau. Tuo et al. (2018) indicated that the SOC and STN stocks increased with increasing MAP in forestland, grassland, and shrubland along a precipitation gradient (280–540 mm) from the west to east of the Loess Plateau. Previous studies mainly considered the effects of the precipitation gradient on the regional C and N distributions or the effects of plantation age at the catchment scale, but few studies have considered the effects of both plantation age and precipitation gradient at the regional scale. Chang et al. (2014) found that the SOC and STN stocks of younger and older forests increased with the MAP from 380 to 650 mm in the Loess Plateau, but their study investigated only soil C and N in the top 20-cm layer. Therefore, it is essential to investigate the SOC and STN variations in the deep layers of forests with different plantation ages along the precipitation gradient, which will contribute greatly to regional soil C and N estimations and provide suggestions for forest management.

In this study, five sites were selected across a south–north transect in the Loess Plateau, and at each site, the SOC and STN stocks in the 0- to 200-cm soil profiles of three black locust stands with different plantation ages, and nearby cropland were measured. The objectives of this study were to (a) compare the SOC and STN stock variations along the precipitation gradient among the different aged forests and cropland, (b) investigate the SOC and STN changes and their correlations after afforestation, and (c) explore the effects of plantation age and climate gradient on the SOC and STN dynamics following afforestation.

2 | MATERIALS AND METHODS

2.1 | Site description

This study was conducted in a south–north transect of the Loess Plateau with a length of 520 km (34.85–38.79°N, 108.10–110.37°E and 1,040–1,300 m a.s.l.). Five sites (including Yijun, Fuxian, Yan'an, Suide, and Shenmu) were selected along the transect to determine the spatial variabilities of SOC and STN (Figure 1). The MAP (1961–2013) increased from 416 mm in Shenmu to 597 mm in Yijun, and nearly 65% of the annual rainfall is concentrated during June–September at all sites. The mean annual temperature (1961–2013) increased from 9.7 °C in the north and 10.6 °C in the south across the transect (Table 1). The landform of all five sites was typical loess and hilly. The soils in Yijun, Fuxian, and Yan'an were all Cambisoils, and those in the Suide and Shenmu sites were composed of Cambisoils and Arenosols or Kastanozems (Nachtergaele, Spaargaren, Deckers, & Ahrens, 2000; Table 1).

Black locust is an N-fixing tree and is one of the most widely distributed afforestation species in the Loess Plateau (Jia, Shao, Zhu, & Luo, 2017). At each site, three black locust forests with different plantation ages were chosen, and the nearby cropland was selected for comparison. The ages of the forests were determined by asking farmers and consulting official records; ages were confirmed by checking the tree rings, which were taken using Haglof increment borers. The forest ages were not exactly the same at the five sites. To make the results comparable, the forests were divided into three age groups at each site, that is, young forest (YF, <15 years), middle-aged forest (MF, 15–25 years), and old forest (OF, >25 years). The definitions of YF, MF, and OF were based on the standard age group classification for broadleaf forests in North China (Xie et al., 2011) and the age ranges of younger and older black locust forests in the Loess Plateau (Chang et al., 2014). The basic information about the forest stands is given in Table S1. The forest and cropland stands were close to each other at each site, and they had similar aspects and angles. The local farmers confirmed that the forest stands had all recovered from being cultivated cropland for more than 30 years; prior to the ecological restoration project, the stands had similar histories and management. Moreover, the soil type and soil texture of the forest and cropland stands were generally the same (Table S2). Therefore, the baselines of the cropland and three forests were assumed to have no differences before revegetation, and the differences in soil C and N between cropland and forests were mainly caused by afforestation (Davidson & Ackerman, 1993; Jia et al., 2012).

The cropland was farmed with maize (*Zea mays* L.), and similar fertilization levels and no irrigation were applied to the cropland at all sites. The black locust was regularly planted, and only the OFs were occasionally thinned for grazing before the "Grain for Green" Program began in 1999. Little interference has occurred in all forest stands after 2000 (Chang et al., 2014). Furthermore, no forest stands have ever been fertilized or irrigated.

2.2 | Field sampling and experimental analyses

The area of the forest stands at the Yijun, Fuxian, and Yan'an sites were large enough, so three plots, each with an area of 10 × 10 m, were selected as soil sampling replicates in each forest stand. In the Suide and Shenmu sites, the forest stand areas were smaller than 0.5 ha, and only one plot (10 m × 10 m) with three sampling points was established. Three plots (1 m × 1 m) were randomly chosen in the cropland stands.

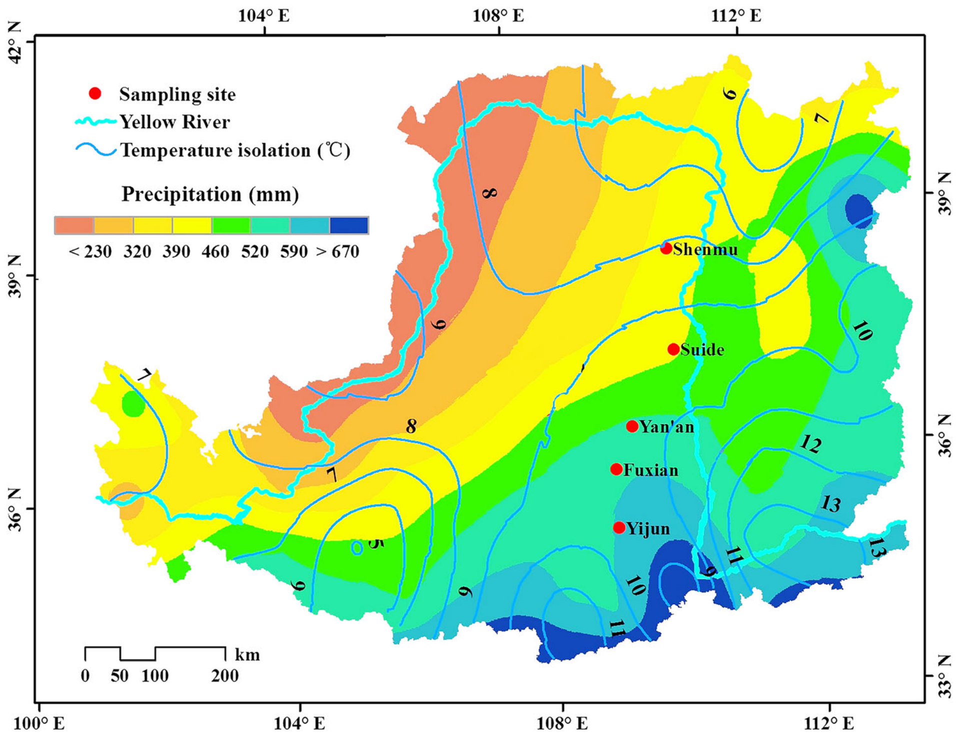

FIGURE 1 Locations of the five sites along the south–north transect in the Loess Plateau, China [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 General information of the five chosen sites across the south–north transect in the Loess Plateau

Site	Longitude	Latitude	Elevation (m)	MAT (°C)	MAP (mm)	ET_0 (mm)	Soil type
Shenmu	110°22′2.9″E	38°47′34.3″N	1,190	9.7	416	1,017	Cambisols and Arenosols
Suide	110°17′20.2″E	37°30′35.3″N	1,040	9.9	452	1,067	Cambisols and Kastanozems
Yan'an	109°31′13.2″E	36°42′29″N	1,178	9.9	520	974	Cambisols
Fuxian	109°10′28 ″E	36°4′18.4″N	1,120	10.2	565	979	Cambisols
Yijun	109°7′13.6″E	35°19′53.2″N	1,300	10.6	597	1,014	Cambisols

Note. The time period for MAT, MAP, and ET_0 was during 1961–2013.

Abbreviations: ET_0, potential evapotranspiration; MAP, mean annual precipitation; MAT, mean annual temperature.

At each point, disturbed soil samples were collected from five layers (0–20, 20–50, 50–100, 100–150, and 150–200 cm), using a soil auger with a diameter of 5 cm. Three soil samples were collected as replicates of each layer in each stand. Each soil sample was air dried and divided into two parts. One part was passed through a 2-mm mesh to measure the particle size composition (%) by laser diffraction (Mastersizer 2000). The other part was passed through a 0.25-mm mesh to measure the SOC concentration (SOCC, g kg^{-1}) by the $K_2Cr_2O_7$–H_2SO_4 oxidation method and the STN concentration (STNC, g kg^{-1}) by the semimicro-Kjeldahl method (Nelson & Sommers, 1982). A soil profile with a depth of 200 cm was dug in the centre of each stand to collect undisturbed soil cores from depths of 0–20, 20–50, 50–100, 100–150, and 150–200 cm (three replicates at each depth), and the bulk density (BD, g cm^{-3}) was measured by a stainless steel cutting ring with a diameter of 5 cm and a length of 5 cm. Stones were rarely encountered when measuring the BD in the five sites. If there were visible stones in the soil core, it was resampled at other points in the dug profile. The soil particle size composition and BD are given in Table S2.

2.3 | Data and statistical analyses

2.3.1 | Calculations of SOC stock, STN stock, and C/N ratio

The SOC and STN stocks (kg/m^{-2}) were calculated according to Grimm, Behrens, Märker, and Elsenbeer (2008):

$$\text{SOC stock} = \sum 0.01 \times \text{SOCC}_i \times \text{BD}_i \times (1 - \text{ST}_i) \times \Delta d_i, \qquad (1)$$

$$\text{STN stock} = \sum 0.01 \times \text{STNC}_i \times \text{BD}_i \times (1 - \text{ST}_i) \times \Delta d_i, \qquad (2)$$

where 0.01 is the unit conversion parameter, the subscript *i* is the number of soil layers, and Δ*d* is the depth of the soil layer (cm). ST is the volumetric percentage of coarse fragments (>2 mm), which could be considered to be negligible according to Liu, Shao, and Wang (2011).

The SOC and STN stocks in the cropland ($SOC_{cropland}$ and $STN_{cropland}$) were considered as the baseline. The SOC and STN stock changes (SOC and STN) indicated the relative changes in the soil C and N after afforestation with respect to cropland, respectively. The SOC and STN were determined by subtracting $SOC_{cropland}$ and $STN_{cropland}$ from the SOC and STN stocks in the forests (SOC_{forest} and STN_{forest}) at each site:

$$\Delta \text{SOC} = \text{SOC}_{\text{forest}} - \text{SOC}_{\text{cropland}}, \qquad (3)$$

$$\Delta \text{STN} = \text{STN}_{\text{forest}} - \text{STN}_{\text{cropland}}. \qquad (4)$$

The C/N ratio is considered to be a sign of the soil N mineralization capacity, which has an important impact on soil C and N cycling. The ratio was calculated as the ratio of SOCC and STNC:

$$\text{C/N} = \text{SOCC}/\text{STNC}. \qquad (5)$$

2.3.2 | Statistical analyses

One-way analysis of variance (ANOVA) was performed to evaluate the significance level of the differences in SOC and STN between different forests or different depths. Linear regressions were carried out to determine the spatial variations in the soil C and N stocks and their changes with MAP. Two-way ANOVA was used to quantify the interaction influences of forest age and MAP on the SOC and STN stocks and the C/N ratio. The correlations between the soil C and N stocks (including the correlations between the SOC and STN stocks and the correlations between the SOC and STN) as well as the variations in the C/N ratio were analysed to investigate the C–N interactions for different forests. All statistical analyses were conducted using SPSS 19.0.

3 | RESULTS

3.1 | Vertical variations in SOC, STN, and C/N ratio

The mean SOC concentrations in the 0- to 200-cm profiles of cropland, YF, MF, and OF were 3.26, 3.61, 3.34, and 3.74 g kg^{-1}(Figure 2a), respectively, and the corresponding mean STNCs were 0.40, 0.38, 0.36, and 0.40 g kg^{-1}, respectively (Figure 2b). The SOCC and STNC showed a clear decreasing pattern with soil depth (Figures 2a and 2b). The SOCC and STNC of the top 20-cm layer were significantly larger than those of the 20- to 200-cm layers ($p < .05$). The SOCC or STNC were not significantly different among the layers in the 20- to 200-cm depth (Figure 2a,b).

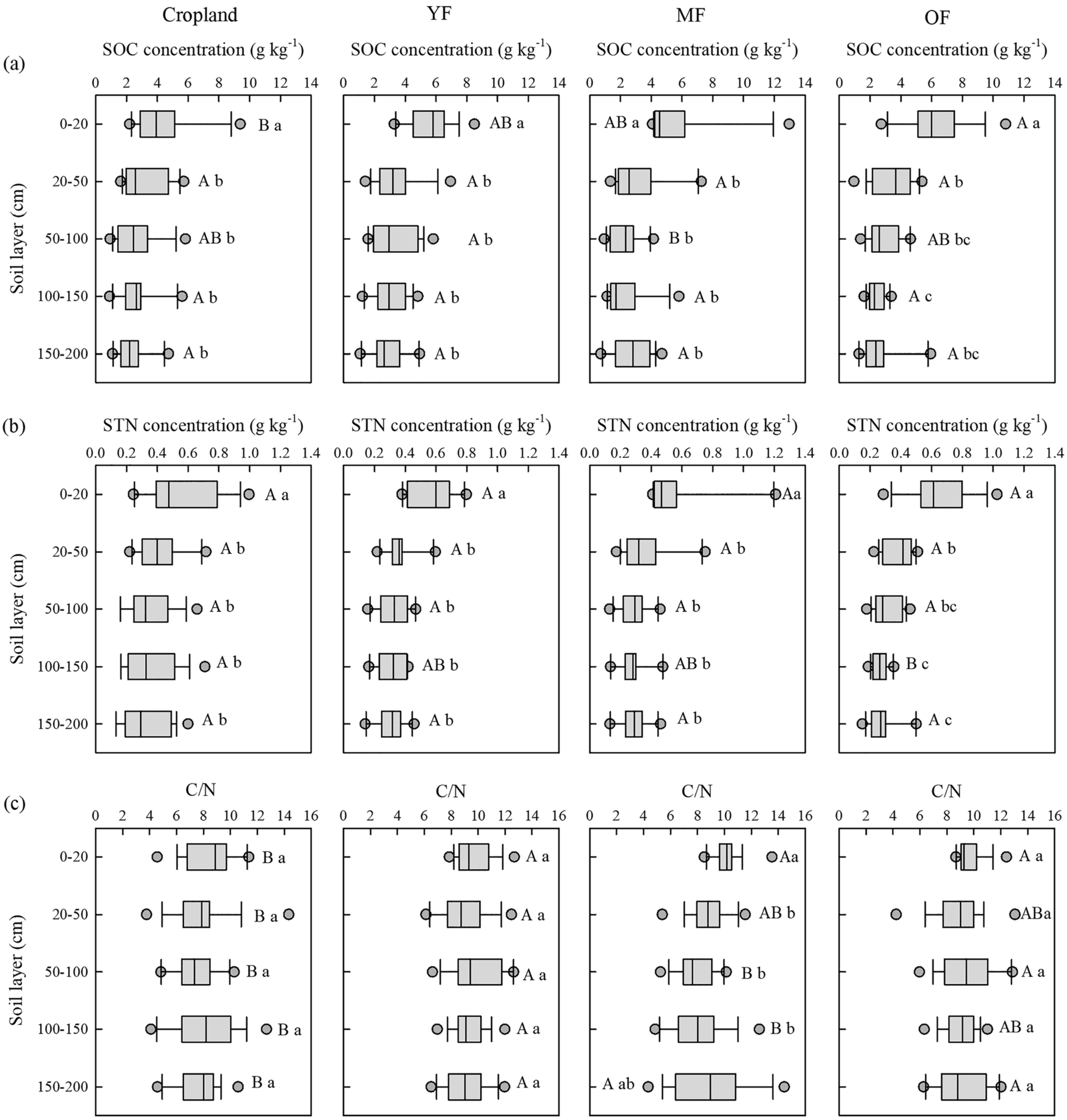

FIGURE 2 Vertical variations in (a) soil organic carbon (SOC) concentration, (b) soil total nitrogen (STN) concentration, and (c) carbon/nitrogen (C/N) ratio in forests of different ages and cropland. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively. The error bars indicate the significance of differences among different sampling sites. The uppercase letters indicate the significance of differences among forests and cropland in the same soil layer ($p < .05$). The lowercase letters indicate the significance of differences among soil layers ($p < .05$)

The SOCC in the 0- to 20-cm soil layer of cropland (4.55 g kg^{-1}) was significantly lower than that of YF (5.54 g kg^{-1}), MF (5.98 g kg^{-1}), and OF (6.27 g kg^{-1}; $p < .05$). The SOCC in the 50- to 100-cm soil layer of MF (2.32 g kg^{-1}) was significantly lower than that of YF (3.27 g kg^{-1}) and OF (2.95 g kg^{-1}; $p < .05$; Figure 2a). The mean STNC in the 100- to 150-cm layer of OF (0.28 g kg^{-1}) was significantly smaller than that of cropland (0.36 g kg^{-1}; $p < .05$; Figure 2b). Except for the above significant differences, the SOCC and STNC in the other layers showed no significant differences among the cropland and forests.

The C/N ratio demonstrated a much smaller vertical variability compared with those of the SOCC and STNC, and the differences in the C/N ratio in the different layers were not significant (Figure 2c). The mean C/N ratio for the 0- to 200-cm profiles of YF, MF, and OF were 9.38, 8.78, and 9.26, respectively, which were significantly larger than the C/N ratio of cropland (7.84; $p < .05$). Therefore, the plantation age significantly affected the SOC concentration in the upper layers and the STNC in the deeper layers ($p < .05$); however, the plantation age had no significant influence on the C/N ratio.

3.2 | Spatial variations in SOC and STN stocks

The SOC stocks in the 0- to 200-cm layers of cropland, YF, MF, and OF were 7.26, 8.26, 6.89, and 8.83 kg m^{-2}, respectively, with STN stocks of 0.92, 0.81, 0.93, and 0.90 kg m^{-2}, respectively. Two-way ANOVA showed that forest age significantly affected SOC stock, STN stock, C/N ratio, ΔSOC, and ΔSTN ($p < .001$; Table 2). The effects of MAP on the SOC and STN stocks as well as the ΔSOC and ΔSTN were also significant ($p < .05$), whereas there was no significant impact of MAP on the C/N ratio ($p > .05$). The two-factor interaction (Age × MAP) significantly influenced the SOC and STN stocks and their changes ($p < .001$), as well as the C/N ratio ($p < .05$; Table 2).

TABLE 2 Two-way analysis of variance of soil organic carbon (SOC) and soil total nitrogen (STN) stocks and their changes following afforestation as affected by forest age and mean annual precipitation (MAP)

Variable	SOC	STN	C/N	ΔSOC	ΔSTN
F					
Age	32.234	37.872	13.802	18.451	14.809
MAP	123.727	485.024	1.130	3.714	79.085
Age × MAP	8.805	24.199	2.482	6.807	4.512
p					
Age	<.001	<.001	<.001	<.001	<.001
MAP	<.001	<.001	.356	.014	<.001
Age × MAP	<.001	<.001	.016	<.001	.001

The SOC stocks in the 0- to 200-cm layers of cropland, YF, and MF showed significant increases with increasing MAP ($p < .05$), whereas there was no significant increase observed for OF (Figure 3c). The regression slopes of the SOC stocks with MAP were 0.031, 0.038, 0.023, and 0.032 for cropland, YF, MF, and OF, respectively (Figure 3c). The increasing trends of the total STN stock in the cropland, YF, MF, and OF profiles were all significant ($p < .05$), with regression slopes of 0.005, 0.003, 0.003, and 0.004, respectively (Figure 3c). The above results showed that the increasing degrees of SOC and STN stocks with MAP were the smallest in MF.

The SOC stocks in the different layers showed variable increasing trends along the precipitation gradient. The SOC stocks in layers within the 20- to 200-cm depth of cropland and the 0- to 200-cm profile of YF increased significantly with increasing MAP ($p < .05$; Figure 3 a). The increase in SOC stocks along the precipitation gradient was significant in only the 20- to 50- and 50- to 100-cm layers of MF and in the 100- to 150-cm layer of OF ($p < .05$; Figure 3a). The STN stocks in cropland and YF increased significantly with MAP in all layers except the 20- to 50-cm layer, whereas there was a significant increase in only the deep layers (150–200 cm) for MF and the middle layers for OF (50–150 cm; $p < .05$; Figure 3b). In summary, there was an age-dependent change in the spatial variations of the SOC and STN stocks across the precipitation gradient.

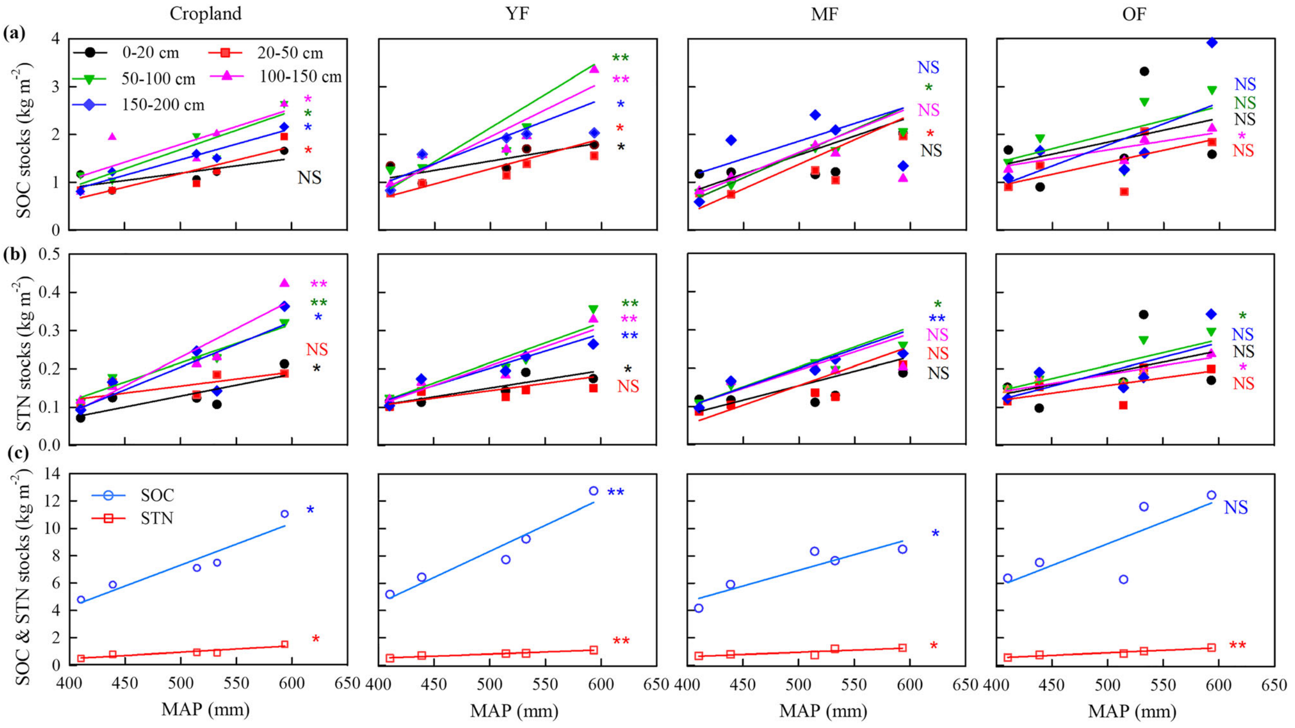

FIGURE 3 Spatial distributions of (a) soil organic carbon (SOC) stock and (b) soil total nitrogen (STN) stock in each soil layer, and (c) the total SOC and STN stocks of the whole profile (0–200 cm) along the precipitation gradient. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively. ** and * indicate the.01 and.05 significance levels of the linear regressions, respectively, and NS indicates that the regression is not significant. MAP, mean annual precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

3.3 | Spatial variations in SOC and STN

The mean SOC in the 0- to 200-cm soil profiles of YF, MF, and OF were 1.08, −0.23, and 1.70 kg m^{-2}, respectively, indicating that OF had the largest amount of C sequestration. The SOC stocks in the 0- to 200-cm soil profile showed decreasing trends with MAP in MF and OF, whereas they showed a slight increase in YF, with regression slopes of −0.012, −0.001, and 0.002, respectively (Figure 4). The SOC in various soil layers of MF and OF showed a decreasing trend with MAP. The SOC in the shallow soil layers (0–20 and 20–50 cm) of YF showed a decreasing trend with MAP, whereas it showed an increasing trend in the deeper soil layers (50–200 cm; Figure 4).

The mean STN stocks in the 0- to 200-cm soil profiles of YF, MF, and OF were −0.05, −0.13, and −0.005 kg m^{-2}, respectively. The STN in the 0- to 200-cm profiles of YF, MF, and OF showed decreasing trends with MAP, and the regression slopes were −0.01, −0.02, and −0.01, respectively (Figure 5). The STN stocks of the three forests showed decreasing trends with increasing MAP in almost all the layers (p > .05), except for the increase in the 20- to 50-cm layers of MF and OF and the 50- to 100-cm layer of YF (Figure 5). Moreover, the decrease in STN stocks with MAP was accompanied by the decrease in SOC stocks, which might represent a limitation of SOC accumulation (Figures 4 and 5).

3.4 | C–N interactions

The SOC and STN stocks were positively correlated, and the correlation was significant in most layers (p < .05), except for the 20- to 50-cm soil layer in cropland and YF, as well as the 100- to 150- and 150- to 200-cm soil layers in MF (Figure 6). The regression slopes between the SOC and STN stocks in the 0- to 200-cm profiles for cropland, YF, MF, and OF were 5.33, 10.67, 7.89, and 11.17, respectively. The regression slopes between the SOC and STN stocks in cropland were smaller than those in the forests in most layers (except for the 50- to 100-cm layer). In terms of a comparison among the forests, the regression slope between the SOC and STN stocks of MF was larger than those of YF and OF in the 0- to 20-cm layer, whereas the slope was the smallest in other layers among the three forests (Figure 6). Figure 7 shows that the SOC and STN were also positively correlated (p < .01), indicating that there were significant interactions between the SOC and STN changes after afforestation. An accumulation of 1-g STN was accompanied by 8.40-, 6.10-, and 10.48-g SOC sequestration for YF, MF, and OF, respectively.

As shown in Figure 8a, the variations in the C/N ratio with MAP were not significant in most soil layers of cropland and forests (p > .05), except for the layers in the 0- to 100-cm depth of YF. The C/N ratio of the whole profile (0- to 200-cm) in cropland, MF, and OF showed decreasing trends with MAP (p > .05), whereas it showed an increasing trend in YF (p > .05; Figure 8b). The results indicated that there were strong C–N interactions following afforestation, which showed different spatial patterns among plantation ages.

4 | DISCUSSION

4.1 | Influences of plantation age and precipitation gradient on SOC and STN changes

The SOC and STN stocks in the 0- to 200-cm soil profiles of forest stands and cropland increased linearly with increasing MAP, and the

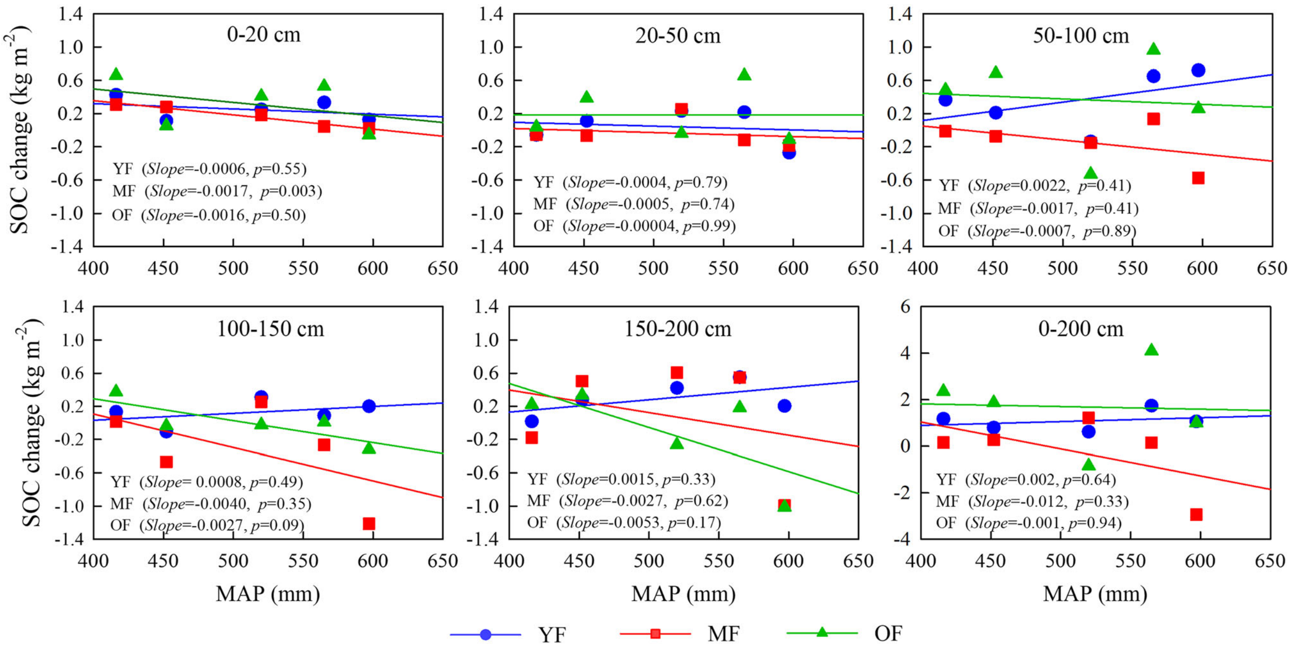

FIGURE 4 Spatial variations in soil organic carbon (SOC) stock changes in different layers following afforestation along the precipitation gradient. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively. MAP, mean annual precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

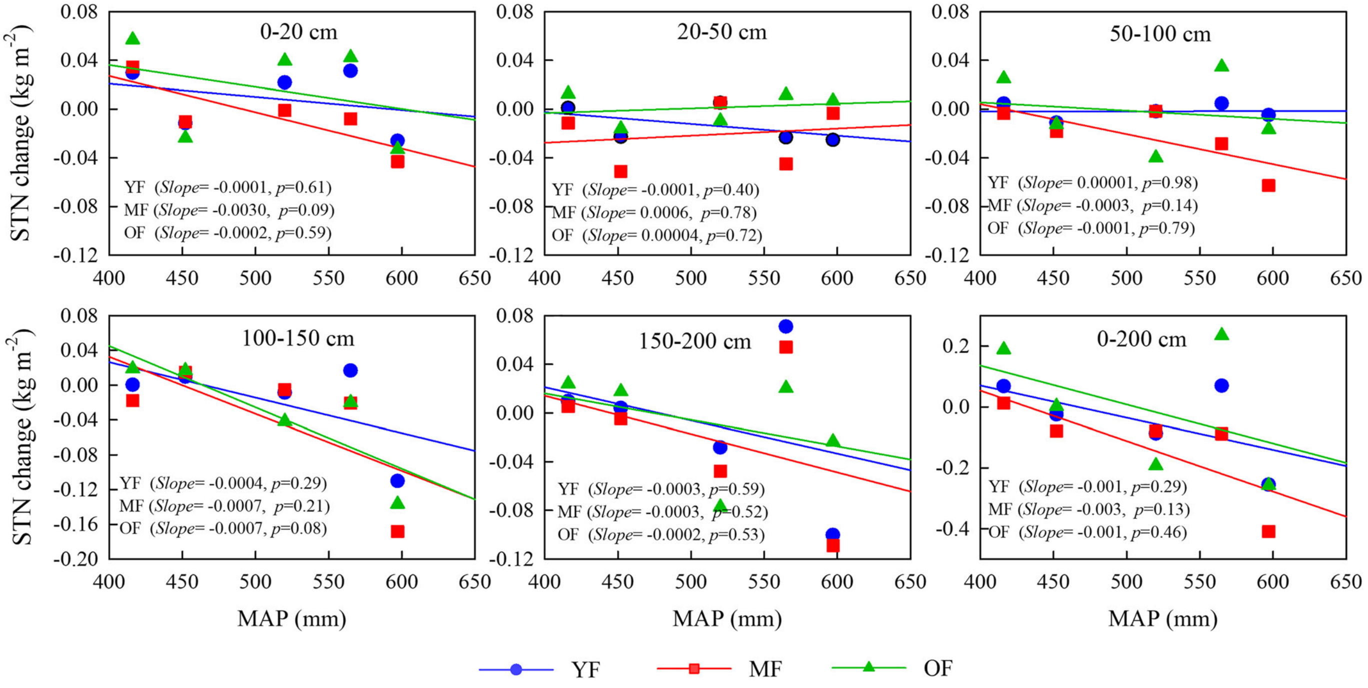

FIGURE 5 Spatial variations in soil total nitrogen (STN) stock changes in different layers following afforestation along the precipitation gradient. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively. MAP, mean annual precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

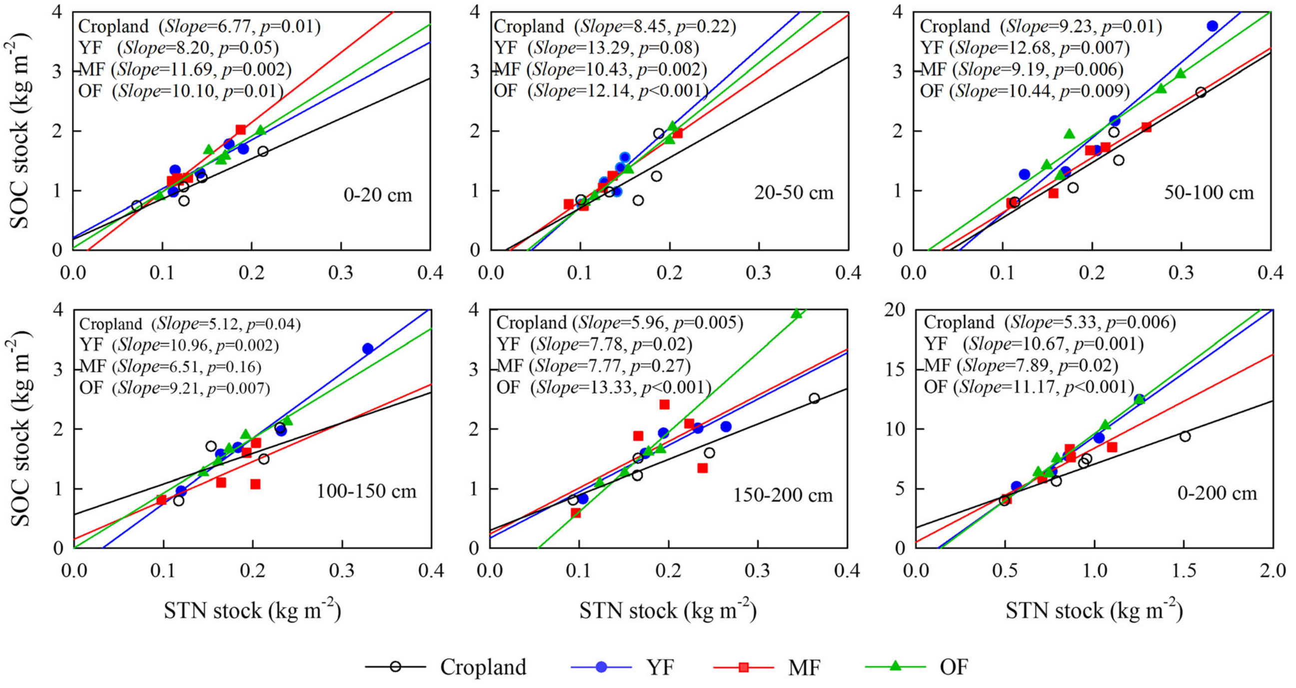

FIGURE 6 Correlations between the soil organic carbon (SOC) and soil total nitrogen (STN) stocks in different soil layers for cropland and forests of different ages. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

regression slopes of cropland and YF were larger than those of the older forests (Figure 3). These results indicated that the SOC and STN in cropland and newly planted forest were more susceptible to human activities and climate factors, whereas those in the older forests were relatively stable (Chen et al., 2007; George, Harper, Hobbs, & Tibbett, 2012). The positive relationships between the SOC and STN stocks and the MAP were related to increasing tree density and aboveground NPP along the precipitation gradient in Table S1 (Miller, Amundson, Burke, & Yonker, 2004). Moreover, the larger SOC and STN stocks at sites with a higher MAP were also related to a larger

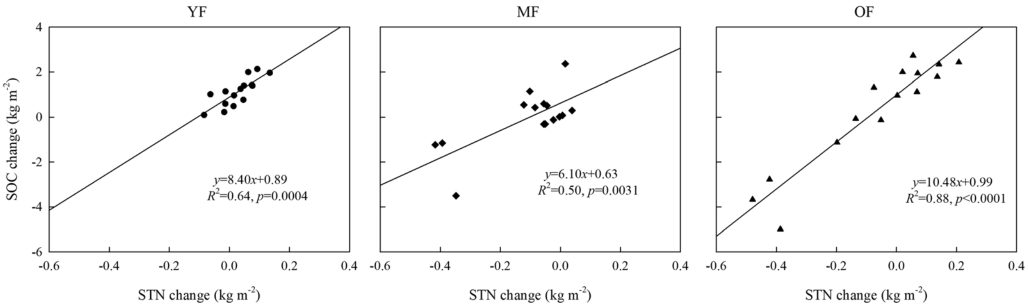

FIGURE 7 Correlations between the soil organic carbon (SOC) and soil total nitrogen (STN) stock changes of the whole soil profile (0–200 cm) following afforestation. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively

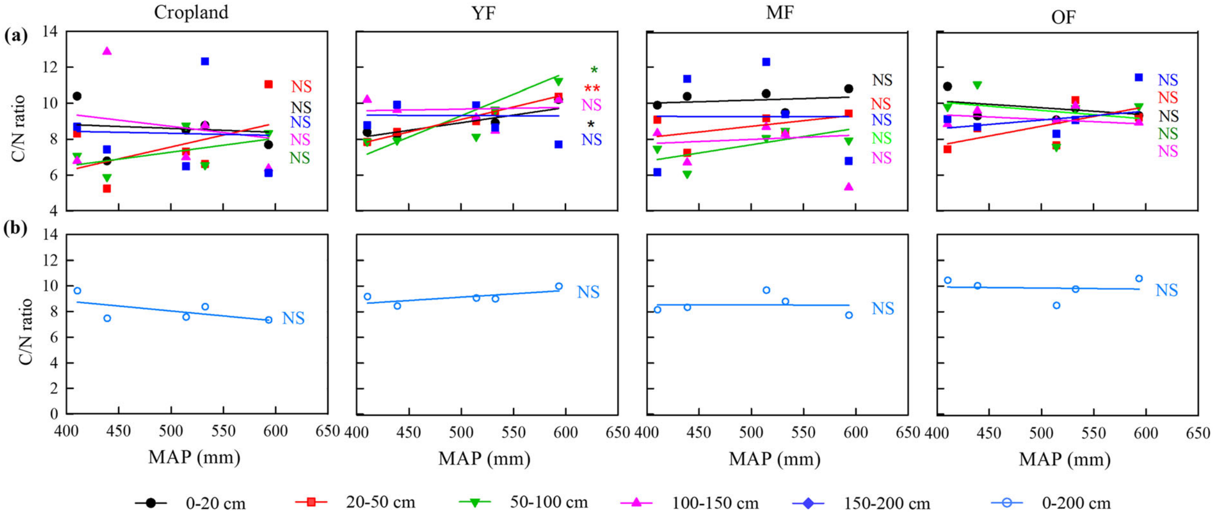

FIGURE 8 Spatial variations in the carbon/nitrogen (C/N) ratio in different soil layers and the whole profile (0–200 cm) along the precipitation gradient. Young forest (YF), middle-aged forest (MF), and old forest (OF) are forests with planting ages of <15, 15–25, and >25 years, respectively. MAP, mean annual precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

percentage of clay particles in the soil, which played a positive role in the SOC and STN accumulation (Wang et al., 2015). The spatial variations in the SOC and STN along the precipitation gradient were affected by multiple factors, including plantation age and soil physical properties, and these factors should be considered simultaneously in the regional C and N estimation (Deng et al., 2016; Peltoniemi et al., 2004; Tuo et al., 2018).

SOC sequestration is related to organic matter decomposition in litter and soils (Keeler, Hobbie, & Kellogg, 2009; Selim et al., 2016), belowground C allocation in root and mycorrhizal exudation (Cusack, Silver, Torn, & McDowell, 2011), and microbial composition and activity (Ramirez, Craine, & Fierer, 2012). STN stock changes depend on biological N fixation, atmospheric N deposition, plant N absorption, and N emission to the atmosphere or groundwater (Li et al., 2012). Therefore, the ΔSOC was determined by the balance of the inputs and the decomposition of biotic residues (Guenet et al., 2018; Peng et al., 2018), whereas the ΔSTN was determined by the N inputs and outputs (Li et al., 2012). In this study, the ΔSOC and ΔSTN in the 0- to 200-cm profiles of the three forests were influenced by precipitation conditions. Generally, both the ΔSOC and the ΔSTN stocks showed decreasing trends with increasing precipitation in most soil layers of the three forests (Figures 4 and 5). The decreasing trends of ΔSOC after afforestation across the precipitation gradient were also found in previous observations (Berthrong et al., 2012; Han et al., 2018; Jia, Yang, et al., 2017). Furthermore, the slopes of the net SOC change responses to MAP in this study were similar to the results of Jackson, Banner, Jobbágy, Pockman, and Wall (2002). However, Tuo et al. (2018) reported that, after shrubland and forestland plantation, the ΔSTN demonstrated a slight increase with MAP. The differences in the above findings was caused by different vegetation types, which can result in different ground surface litters and root distributions in subsoil layers, further causing different SOC and STN sequestration capacities between the surface and deep soils (Berthrong et al., 2012; Fu, Shao, Wei, & Horton, 2010).

The plantation age was a critical factor affecting the SOC and STN dynamics after afforestation (Deng et al., 2016; Wei, Shao, Fu, & Horton, 2010). Generally, the SOC stock was found to decrease during the initial period after afforestation and then increase until net gains were formed (Chang et al., 2014; Yang et al., 2011). In this study, the mean SOC stock was the largest in OF, whereas it was smallest in MF. This result indicated that the older plantation had the strongest soil C sequestration capacity, whereas the middle-aged stands had more NPP and most of the C in the whole ecosystem changed to biomass accumulation (Holmes & Matlack, 2018). The decrease in soil C during the initial stage of afforestation was mainly because the soil C input was not enough to compensate for the continuous decomposition of biotic residues inherited from previous cropland (Li et al., 2012).

The STN of YF, MF, and OF varied in similar ways along the precipitation gradient, and the values of STN were negative in most sites in this study. The negative values were mostly due to high N demand in the active growth of the forest and limited N inputs to the soil as well as by the regular addition of N fertilizer to cropland (Cusack et al., 2011; Zhang et al., 2018). For cropland, N fertilization was the major source of input, and for forests, the N input also came from biological N fixation (Aranibar et al., 2004; Peng et al., 2018). Although the black locust is an N-fixing species, the short-term N fixation was limited and insufficient for self-uptake because the N fixation required a long-term period of more than 30 years (Li et al., 2012). Moreover, the SOC and STN stocks of poplar were found to recover to the levels observed before afforestation after 15 years of plantations in Northeast China (Mao, Zeng, Hu, Li, & Yang, 2010). The potential mechanisms in relation to the STN stock changes after afforestation still need further investigation.

4.2 | C–N interactions following afforestation along the precipitation gradient

Although the mechanisms controlling soil C and N accumulations are different, the spatial distributions of the soil C and N accumulations are generally similar (McLauchlan, 2006). Many studies have documented significant positive correlations between SOC and STN (Wang et al., 2017), and both the SOC and STN stocks increased with increasing MAP in this study. However, the C/N ratio in the three forest plantations and cropland demonstrated weak decreasing trends (Figure 8), indicating higher SOC accumulation rates than STN accumulation rates in sites with lower MAP. This result suggested that the N limitations on soil C accumulation were more significant in the drier regions than those in the wetter regions due to water limitation (Chang et al., 2014; Kirschbaum, Guo, & Gifford, 2008; Tuo et al., 2018). The N addition in drier areas could enhance SOC sequestration, mainly by increasing the dry weight of the organic soil horizon and maintaining the C/N ratios (Evans et al., 2006; Luo et al., 2004). The physical and chemical protection of SOC from soil microaggregates and minerals also increases SOC sequestration, according to Tan et al. (2017). Moreover, soil N additions may reduce the microbial decomposition of SOC and increase soil C storage (Riggs, Hobbie, Bach, Hofmockel, & Kazanski, 2015).

The C–N interactions were also affected by plantation age (Liu et al., 2018; Wei et al., 2009). In this study, the SOC and STN stocks in the 0- to 200-cm soil profiles of the forest plantations and cropland were significantly correlated, and the regression slopes of cropland were smaller than those of forest plantations (Figure 6). This result indicated that the cropland had larger STN stocks and smaller SOC stocks than those of perennial forests, as the biomass was regularly harvested every year. The comparison between forests of different ages showed that the C/N ratios in YF and OF were significantly larger than those in MF in the 50- to 150-cm soil layers ($p < .05$), which is the depth at which the fine roots are mainly concentrated. This result was consistent with the variations in the ΔSOC and ΔSTN stocks after afforestation, which showed initial declines from preafforestation stands and recovery after more than 30 years of afforestation (Zhang et al., 2018). Therefore, long-term restoration (more than 25 years) of black locust forest is needed to obtain the benefits of soil C and N sequestration.

4.3 | Implications and further scopes

This study investigated the effects of forest age on SOC and STN changes along a precipitation gradient across a south–north transect of the Loess Plateau. The results had some important points in terms of application. First, the large-scale spatial distributions of the SOC and STN stocks in black locust forests with different ages and precipitation conditions were demonstrated to a depth of 200 cm, which provided useful parameters and available data for evaluations of regional soil C and N stocks. Second, the consideration of both plantation age and precipitation gradient for SOC and STN stock changes was important, especially in understanding the influences of water limitation on soil C and N accumulation at different stages of forest growth. This consideration was also useful for the determination of N limitation and sustainability of regional soil C sinks. Third, the results provided suggestions for developing optimizing strategies for black locust afforestation and revegetation planning across the Loess Plateau. MF and OF generally had larger SOC and STN stocks than those of YF at all sites along the precipitation gradient, whereas the tree density decreased as the forest plantation became older or as the precipitation decreased. Therefore, appropriate thinning should be carried out in MF and OF to obtain optimal C and N sequestration in areas with limited precipitation.

The mechanisms of soil C accumulation following afforestation along the climate gradient and the N regulations still require further study. First, more sampling sites and longer forest age sequences should be considered to substantially reveal the effects of plantation age and climate gradient on regional C and N dynamics. Second, more vegetation features, such as root and stem biomass as well as soil microbial characteristics, are essential to investigate the soil C–N variations and their interactions following ecological restoration and climate change. Furthermore, in addition to black locust, more tree species should be selected to fully study the promoting effects of afforestation on soil C and N accumulations.

5 | CONCLUSIONS

In this study, the spatial distributions of the SOC and STN stocks in the 0- to 200-cm depth of black locust forests of different ages and nearby cropland were investigated along a precipitation gradient from the north to the south across the Chinese Loess Plateau. Plantation age significantly affected the SOCC in the upper layers and the STNC in the deeper layers ($p < .05$), but plantation age had no significant influence on the C/N ratio. The two-factor interaction (Age × MAP) significantly influenced the SOC and STN stocks and their changes ($p < .001$) as well as the C/N ratio ($p < .05$). The SOC and STN stocks of YF, MF, and cropland showed significant increases with increasing MAP ($p < .05$), whereas the SOC and STN in MF and OF showed decreasing trends along the precipitation gradient. The SOC and STN variations following afforestation were age dependent across the precipitation gradient. The interactions between the SOC and STN changes after afforestation showed different spatial patterns among plantation ages. These results demonstrated the great importance of both plantation age and precipitation gradient in assessing the influences of afforestation on SOC and STN changes, which should be considered in future C and N estimations.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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