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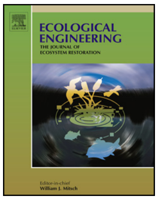

Effects of age and land-use changes on soil carbon and nitrogen sequestrations following cropland abandonment on the Loess Plateau, China

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ABSTRACT

Vegetation restoration and revegetation on land abandonment of cropland has a major impact on the landscape of the Loess Plateau in China. Such processes can alter soil carbon (C) and nitrogen (N) pools and cycling. However, few studies have examined the effect of cropland abandonment on soil C and N sequestration in various land-use types over time. We studied the effects of age and land-use change types on soil C and N sequestration in top 1-m soil depth in the transition from forest to grassland in the center of the Loess Plateau. The results show that age as well as land-use change types had a significant effect on soil C and N sequestrations. Soil C and N sequestrations in the surface soils (0–10 cm) had always increased since cropland abandonment. In the first 10 years, the orchard (OL) and man-made grassland (alfalfa) had higher soil C and N sequestrations than the other types of land uses, such as natural grassland (NG), shrubland (SL), orchard (OL) and woodland (WL). Moreover, in the later stage since cropland abandonment (>20 years), the SL had the high soil C and N sequestrations followed by WL and NG. In addition, the correlations between soil C and N sequestrations were greater in surface soil layers than that in deeper layers, and soil C sequestration was approximately 8–10 times that of soil N sequestration after cropland abandonment. Our study suggests that to get long-term (>20 years) soil C and N sequestration benefits, planting shrubs is a better restoration type in the transition from forest to grassland than natural grassland and woodland on the Loess Plateau, and orchard and man-made grassland (alfalfa) influenced by fertilization also have a good soil C and N sequestration benefits in the short time (<20 years) .

1. Introduction

Soils has twice as much carbon (C) stored in the soils as in the atmosphere, which play a major role in global C cycles (Davidson et al., 2000). Whether soils act as C sinks or sources has become a major focus of research on global climate change (Degryze et al., 2004; Laganière et al., 2010). Local land-use changes can play an important role in environmental and ecological changes, thus contributing to the global change (IPCC, 2007). Reports from around the world indicate that the soil organic carbon (SOC) declines by 20–43% after natural forest or perennial grassland is converted to agricultural land (Don et al., 2011; Wei et al., 2014a). In contrast, the conversion of cropland into forest or grassland has been shown to increase SOC by increasing C derived from new vegetation, thus simultaneously decreasing C loss from decomposition and erosion (Laganière et al., 2010; Shi et al., 2013; Deng et al., 2016). Thus, afforestation and revegetation have been proposed as effective methods for reducing atmospheric CO_2 due to C sequestration in vegetation and soils (UNFCCC, 2009; IPCC, 2007).

Terrestrial carbon–nitrogen (C–N) interactions have attracted considerable interest because of their importance in determining whether the C sink in land ecosystems could be sustained over the long term (Reich et al., 2006). It has been suggested that nitrogen (N) dynamics are a key parameter in regulating terrestrial C sequestration in the long term (Luo et al., 2004). Increased N deposition could reduce atmospheric CO_2 by stimulating forest biomass accumulation (Giardina et al., 2003). Specifically, C sequestration will be sustainable in land ecosystems if it allows for increased N inputs into an ecosystem (Rastetter et al., 1997). In contrast, N limitation would directly constrain terrestrial C sequestration (Schlesinger

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and Lichter, 2001), a process that is fundamental to either mitigating or deferring global warming (Schlesinger and Lichter, 2001). Globally, Yang et al. (2011) have stated that substantial increases in C pools over age sequence are accompanied by N accretion in forest ecosystems. Therefore, there is a need to identify and describe biogeochemical cycles at the regional spatio-temporal scale, which is the scale at which landscape policies are implemented. Elucidating N dynamics in soils has important implications both for the sustainable management of regional land resources and for predictions of future C and N cycling globally.

Recently, many studies have examined the dynamics of soil C and N stocks following vegetation restoration (Knops and Tilman, 2000; Yang et al., 2011; Li et al., 2012). However, different studies have obtained variable results. For example, Deng et al. (2014) reported that soil C stock first declined in the initial stage and then increased after cropland abandonment. Morris et al. (2007) observed that top 1-m soil C stock was accumulated following afforestation on abandoned cropland, while Smal and Olszewska (2008) documented that soil C stock has significantly decreased in Scots pine (*Pinus silvestris* L.) forests along sandy post-arable soils. In addition, Sartori et al. (2007) reported that mineral soil C stock exhibits an insignificant change during forest stand development. Moreover, Knops and Tilman (2000) found that N accumulated in surface soil (0–10 cm) remained unchanged in subsoil (10–60 cm) following afforestation of cropland abandoned for 60 years. Li et al. (2012) found that soil N stocks decreased after afforestation with pine but increased with hardwood afforestation. However, the dynamic pattern is still unclear because different land-use conversion types and soil depths were mixed together, and there were large differences among depths and land-use conversion types in temporal C and N stock changes. In addition, because the relationships between soil C and N stock and climate, land-use types and soil properties in different soil depths have never been examined, the implications for the depth distributions of soil C and N are still unknown. Thus, our understanding of soil C and N dynamics in different soil depths and land-use conversion types remains incomplete.

The Loess Plateau is suffering severe soil and water losses (Liu et al., 2007). To control soil erosion and restore ecosystems, China has launched the "Grain for Green" Programs (GGP) aimed at restoring degraded cropland to forest and grassland. In the study area, the cropland had already been abandoned, and the process of natural and artificial restoration was underway. Although the initial goal of the GGP was to control soil erosion, the program strongly affects C and N cycling in soil. Consequently, many studies have focused on changes to soil C and N accumulation following cropland abandonment on the Loess Plateau (Zhang et al., 2013a; Deng et al., 2013). However, those studies only focused on one simple type of conversion and obtained inconsistent results. Therefore, a comprehensive study of soil C and N dynamics that considers different land-use conversion types (e.g., forest, shrub and grassland) at different ages is greatly needed. Our study aims to examine: (1) dynamics of soil C and N sequestrations in different agricultural and forest land uses, (2) the effects of restoration age as result of cropland abandonment on soil C and N sequestrations and (3) the relationship between soil C and N sequestrations estimated based on changes in C and N stocks at different times following cropland abandonment.

2. Material and methods

2.1. Study area

All study sites are located in Ansai County, Shaanxi Province, China (36°30′45″–37°19′31″N, 108°5′44″–109°26′18″E; 1,012–1,731 m a.s.l.) in the center of the Loess Plateau (Fig. 1). The study area is characterized by a semi-arid climate and a deeply incised hilly-gully Loess landscape. The mean annual temperature range is 9.1 ± 0.1 °C (1970–2010), and the mean annual precipitation is 503 ± 15 mm (1970–2010), of which 70% falls between July and September. The sand, silt and clay contents are 65%, 24% and 11%, respectively, and soil pH ranged from 8.3 to 8.9.

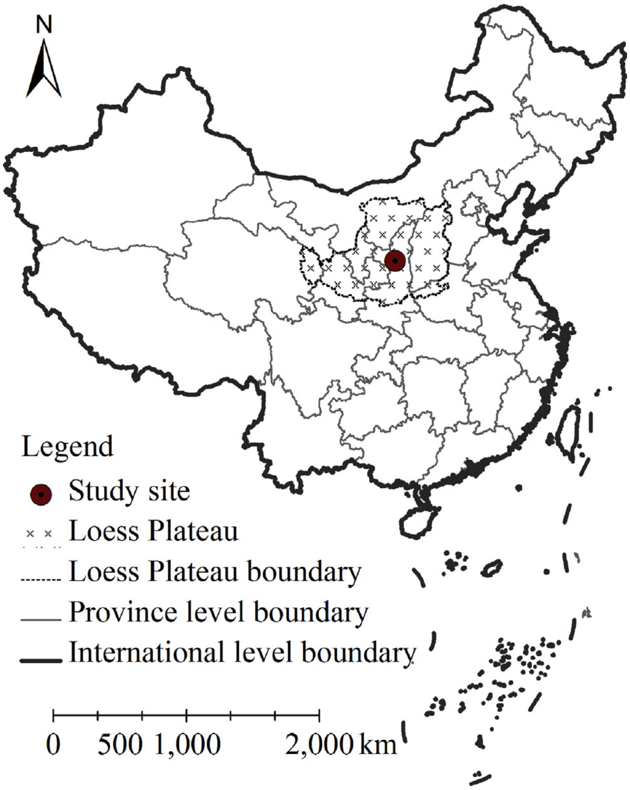

Fig. 1. Location of the study area (Ansai County, China).

2.2. Sampling design and data collection

In our study, we used the "space" for "time" method to study vegetation restoration/revegetation changed over time, which is a common method used to monitor plants and soils under similar climatic conditions following the sequence of vegetation development (Sparling et al., 2003; Li et al., 2007; Deng et al., 2013).

We conducted field surveys between July 10 and September 10 in 2011 and 2012 when the plant community biomass peaked. In total, we have chosen five land-use change types after cropland abandonment, and the sampling areas of the communities involved were determined according to their types. There were three 20 m × 20 m plots chosen in each forestlands (*Robinia pseudoacacia*), three 10 m × 10 m plots chosen in each shrublands (*Caragana microphylla*, *Hippophae rhamnoides*), three 2 m × 2 m plots chosen in each herbaceous communitiy (*Artemisia sacrorum*, *A. capillaries*, *A. giraldii*, *Aneurolepidium dasystachys*, *Bothriochloa ischaemum*, *Heteropappus altaicus*, *Lespedeza bicolor*, *Stipa bungeana*, *Setaria viridis*, etc.), three 2 m × 2 m plots chosen in each man-made alfalfa grassland (*Medicago sativa*), and three 10 m × 10 m plots chosen in each apple orchard, respectively. Each plot was at least 30 m from the other plots. We randomly selected 95 soil sites from growing vegetation between 1 and 56 years old. The restoration ages of each land-use types were achieved from the descriptions found in contracts between local farmers and local governments established. All of the stages of vegetation restoration or revegetation in this study were the result of cropland abandonment. In total, the number of natural grasslands (NG), woodlands (WL), shrublands (SL), orchards (OL) and man-made grasslands (MG) we have surveyed were 43, 16, 23, 9 and 4, respectively. The age ranges of the NG, WL, SL, OL and MG were from 1 to 34, from 5 to 56, from 5 to 47, from 5 to 20 and from 5 to 10, respectively. The restoration ages of the five land-use types since cropland abandonment were divided into three groups as follows: 0–10, 10–20 and >20 years. In addition, we selected four cropland sites for comparison (CK) because the five land-use types were converted from croplands. In the study area, the maize (*Zea mays*), millet (*Setaria italica*) and soybean (*Glycine max*) had been widely seeded and cultivated for more than 50 years before cropland conversions.

Soil samples were taken at the sampling plots as described above. Soil samples from five soil layers (0–10, 10–20, 20–30, 30–50 and 50–100 cm) were collected using a soil drilling sampler (4 cm inner diameter). After removing the ground litters in each plot, soil samples from the same soil layers within one plot were then mixed to form one soil sample (5 replicates), and then soil samples were air dried and passed through a 2-mm screen, meanwhile the roots and other debris were removed before the soil physical and chemical properties were measured. The soil bulk density (BD) of the soil sampling sites were measured by the different soil layers using a soil bulk sampler with a 5.0-cm-diameter and 5.0-cm-high stainless steel cutting ring (3 replicates) at points adjacent to the soil sampling plots by measuring the original volume of each soil core and the dry mass after oven drying at 105 °C.

2.3. Physical and chemical analysis

Soil BD was calculated depending on the volume of the core sampler and the oven-dried weight of the undisturbed soil samples. Soil organic carbon (SOC) content was measured using the dichromate oxidation method (Nelson and Sommers, 1982) and soil total nitrogen (STN) content was measured using the Kjeldahl method (Bremner, 1996).

2.4. Calculation of soil C and N stocks

Because there was no coarse fraction (>2 mm) in the soil samples, we used the following equation to calculate soil C stock (Cs):

$$\mathrm{Cs} = \frac{\mathrm{SOC} \times \mathrm{BD} \times D}{10} \tag{1}$$

where, Cs is soil C stock ($\mathrm{Mg\,ha^{-1}}$), BD is soil bulk density ($\mathrm{g\,cm^{-3}}$), SOC is soil organic carbon content ($\mathrm{g\,kg^{-1}}$) and D is the thickness of the sampled soil layer (cm).

The study used the following equation to calculate soil N stock (Ns):

$$\mathrm{Ns} = \frac{\mathrm{STN} \times \mathrm{BD} \times D}{10} \tag{2}$$

where, Ns is soil N stock ($\mathrm{Mg\,ha^{-1}}$), BD is soil bulk density ($\mathrm{g\,cm^{-3}}$), STN is soil total N content ($\mathrm{g\,kg^{-1}}$) and D is the thickness of the sampled soil layer (cm).

2.5. Calculation of soil C and N sequestrations

In the study, we set the C and N stock of the cropland as the baseline for calculating C and N sequestration after cropland abandonment. We used the following formula to calculate C and N sequestrations:

$$\text{C sequestration}\,(\Delta\text{Cs, in Mg ha}^{-1}):\ \Delta\mathrm{Cs} = \mathrm{C}_{\mathrm{LU}n} - \mathrm{C}_{\mathrm{LU0}}, \tag{3}$$

and

$$\text{N sequestration}\,(\Delta\text{Ns, in Mg ha}^{-1}):\ \Delta\mathrm{Ns} = \mathrm{N}_{\mathrm{LU}n} - \mathrm{N}_{\mathrm{LU0}} \tag{4}$$

where, $\mathrm{C_{LUn}}$ is soil C stock at the site after cropland abandonment ($\mathrm{Mg\,ha^{-1}}$), $\mathrm{C_{LU0}}$ is soil C stock at the initial stage of cropland ($\mathrm{Mg\,ha^{-1}}$), $\mathrm{N}_{\mathrm{LU}n}$ is soil N stock at the site after cropland abandonment ($\mathrm{Mg\,ha^{-1}}$) and $\mathrm{N_{LU0}}$ is soil N stock at the initial stage of cropland ($\mathrm{Mg\,ha^{-1}}$).

2.6. Statistical analysis

Two-way ANOVA was performed to test the effects of land-use changes (NG, WL, SL, OL and MG) and ages (years since cropland abandonment) on soil C and N sequestrations. We have carried out normality analysis and the test of homogeneity of variance before ANOVA analysis. Significance was evaluated at the 0.05 level ($P < 0.05$). When significance was observed at the $P < 0.05$ level, Tukey's post hoc test was used to carry out the multiple comparisons. Pearson correlations was used to analysis the correlations between soil C and N sequestrations and age since cropland abandonment in each soil depth. And a Generalized Linear Model (GLM) were used to carry out regression analysis on the relationship between soil C and N sequestration and age since cropland abandonment at each soil layer of 0–100 cm soils. In the study, the data used in data analysis have not undertaken any data transformations. Figures were created using SigmaPlot version 10.0 (Systat software Inc., San Jose, CA, USA), All of the statistical tests were carried out using SPSS version 17.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Difference of soil C and N sequestration in various ages

Both age and land-use types had significant effect on soil C and N sequestration (Table 1). Soil C and N sequestration in each soil depths exhibited similar characteristics (Figs. 2 and 3). However, soil C and N stocks had different characteristics in different soil depths following cropland abandonment (Figs. 2 and 3). Soil C and N sequestrations of 0–10 cm soils had strongly increased since cropland abandonment (Fig. 2A and B). Moreover, soil C and N sequestrations in OL and MG had always increased in all soil layers (Figs. 2 and 3). Overall, in the subsoils (>20 cm), soil C and N sequestrations in the NG, WL and SL showed the trends of first declining and then increasing after cropland abandonment; meanwhile, there had some difference due to affect by age and soil depths (Figs. 2 and 3). In addition, in the same period since cropland abandonment, the five land-use change types had significant differences in the soil C and N sequestrations changes (Figs. 2 and 3). In the early stage (0–10 years) since cropland abandonment, the OL and MG had the higher soil C and N sequestrations than other three types of NG, WL and SL. Moreover, in the later stage since cropland abandonment (>20 years), the SL had the higher soil C and N sequestrations than the WL and NG (Figs. 2 and 3).

3.2. Effects of restoration age on soil C and N sequestrations since cropland abandonment

The correlation analysis showed that the correlations between soil C or N sequestrations and restoration age varied with soil depth, and this is different for each single land-use change type (Table 2). In NG, WL and SL, soil C and N sequestrations had positive correlations with age in every soil depth and had significant positive correlations in the topsoil depth of the NG (0–30 cm) and WL (0–50 cm; $P < 0.05$), but in the subsoil depths of 50–100 cm, the positive correlations were not significant ($P > 0.05$; Table 2). For SL, only in the subsoil depths (30–100 cm), soil C sequestrations had significant positive correlations with age (Table 2). In addition, soil C and N sequestrations in the OL and MG had no significant correlations with age in every soil depth ($P > 0.05$; Table 2).

Table 1
Tests of between-subject effects of soil C and N sequestration linkage with age (years since cropland abandonment) and land use types.

Source	df	C sequestration ($Mg\,ha^{-1}$)		N sequestration ($Mg\,ha^{-1}$)	
		F	Sig.	*F*	Sig.
Age	2	35.85	0.000***	28.67	0.000***
Land-use types	4	15.25	0.000***	25.709	0.000***
Age × Land use types	5	3.37	0.005**	2.519	0.029*

[*] Indicates a significant difference at the 0.05 level ($P < 0.05$).
[**] Indicates a significant difference at the 0.01 level ($P < 0.01$).
[***] Indicates a significant difference at the 0.001 level ($P < 0.001$).

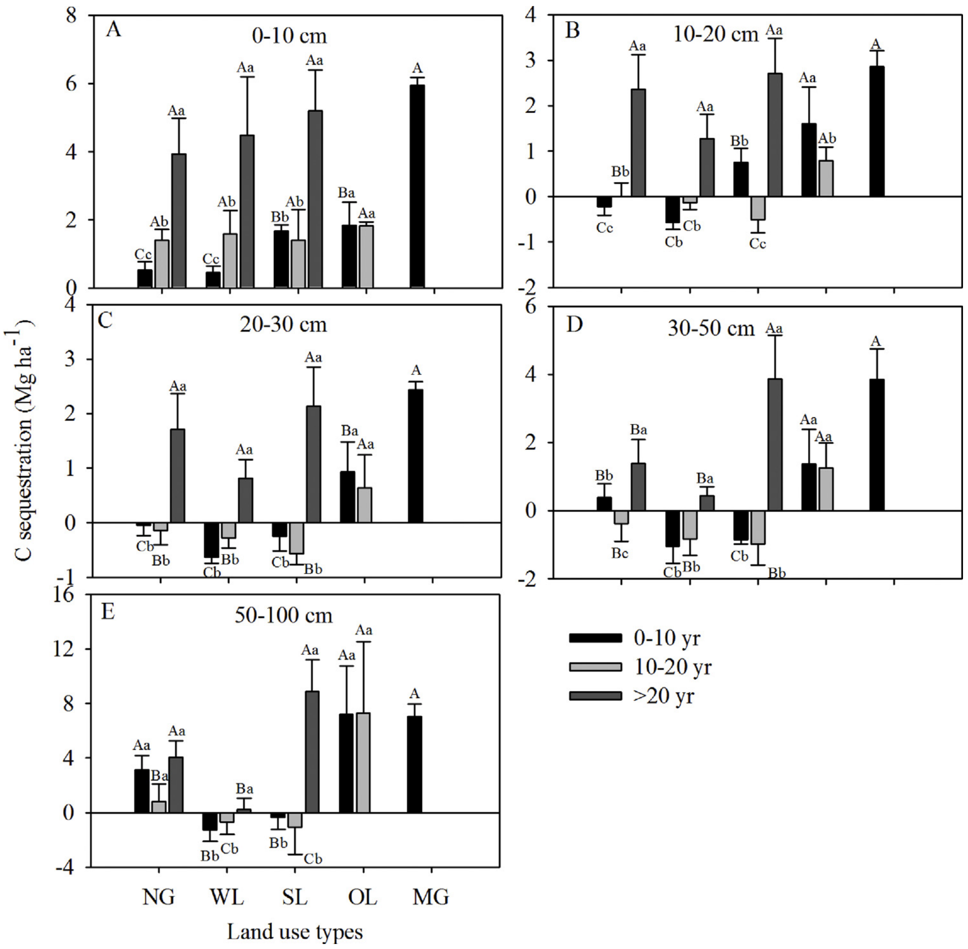

Fig. 2. Soil C sequestrations change with age since cropland abandonment in different land-use change types. Note: NG = natural grassland, WL = woodland, SL = shrubland, OL = orchard and MG = manual grassland. The values represent the means ± SE. Different lower-case letters above the bars mean significant differences among different ages within the same land-use types ($P < 0.05$), and different upper-case letters above the bars mean significant differences in the same ages among different land-use types ($P < 0.05$).

Table 2
Pearson correlations between soil C and N sequestrations and age since cropland abandonment in each soil depth.

Soil depths (cm)	Soil C or N sequestrations ($Mg\,ha^{-1}$)	Land-use types				
		NG	WL	SL	OL	MG
0–10	ΔC_s	0.557** ($n = 43$)	0.8** ($n = 16$)	0.344 ($n = 23$)	0.115 ($n = 9$)	0.942 ($n = 4$)
	ΔNs	0.530** ($n = 43$)	0.331 ($n = 16$)	0.405 ($n = 23$)	–0.551 ($n = 9$)	0.648 ($n = 4$)
10–20	ΔCs	0.543** ($n = 43$)	0.910** ($n = 16$)	0.358 ($n = 23$)	-0.129 ($n = 9$)	0.312 ($n = 4$)
	ΔNs	0.477** ($n = 43$)	0.8** ($n = 16$)	0.281 ($n = 23$)	-0.541 ($n = 9$)	-0.062 ($n = 4$)
20–30	ΔCs	0.465** ($n = 43$)	0.860** ($n = 16$)	0.384 ($n = 23$)	0.164 ($n = 9$)	0.912 ($n = 4$)
	ΔNs	0.387* ($n = 43$)	0.730** ($n = 16$)	0.253 ($n = 23$)	-0.273 ($n = 9$)	0.725 ($n = 4$)
30–50	ΔCs	0.267 ($n = 43$)	0.512* ($n = 16$)	0.44* ($n = 23$)	0.177 ($n = 9$)	0.398 ($n = 4$)
	ΔNs	0.314* ($n = 43$)	0.615* ($n = 16$)	0.277 ($n = 23$)	-0.229 ($n = 9$)	0.725 ($n = 4$)
50–100	ΔCs	0.158 ($n = 43$)	0.138 ($n = 16$)	0.512* ($n = 23$)	0.016 ($n = 9$)	-0.013 ($n = 4$)
	ΔNs	0.148 ($n = 43$)	0.109 ($n = 16$)	0.399 ($n = 23$)	-0.333 ($n = 9$)	0.232 ($n = 4$)

Note: NG, natural grassland, WL, woodland, SL, shrubland, OL, orchard, MG, manual grassland.
[*] Correlation is significant at the 0.05 level (2-tailed; $P < 0.05$); (value) indicates the number of observations.
[**] Correlation is significant at the 0.01 level (2-tailed; $P < 0.01$).

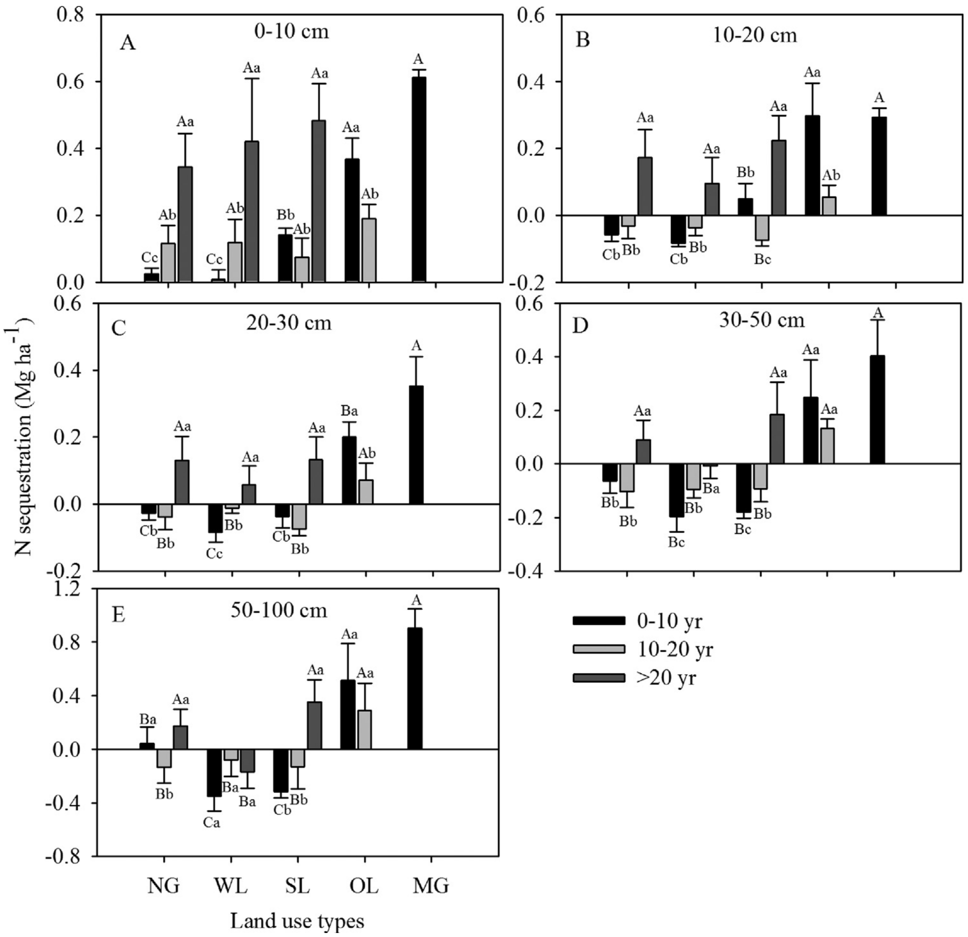

Fig. 3. Soil N sequestrations change with age since cropland abandonment in different land-use change types. Note: NG = natural grassland, WL = woodland, SL = shrubland, OL = orchard and MG = manual grassland. The values represent the means ± SE. Different lower-case letters above the bars mean significant differences among different ages within the same land-use types ($P < 0.05$), and different upper-case letters above the bars mean significant differences in the same ages among different land-use types ($P < 0.05$).

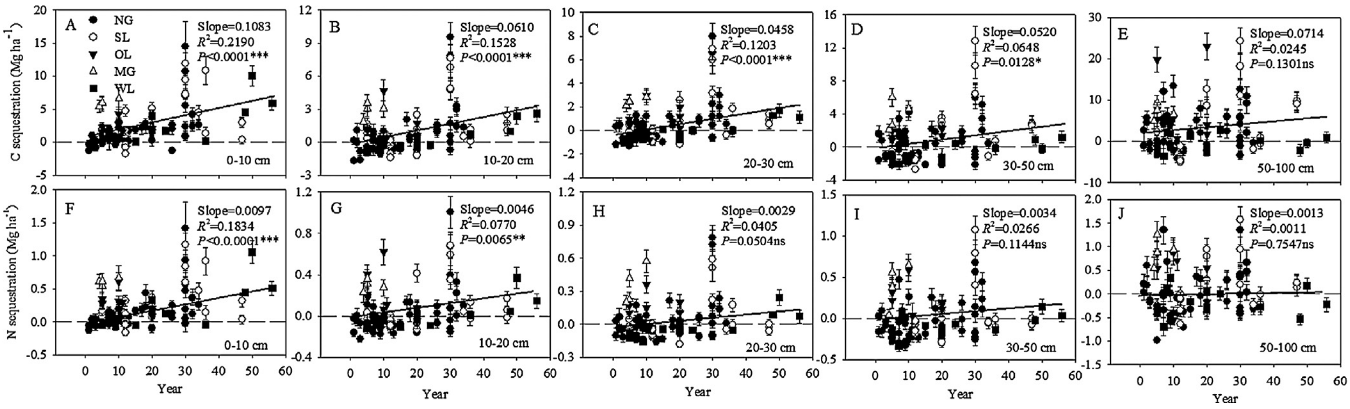

Fig. 4. The relationship between soil C and N sequestration and age since cropland abandonment at each soil layer of 0–100 cm soils. Note: NG = natural grassland, SL = shrubland, OL = orchard, MG = manual grassland and WL = woodland. The dashed lines indicate the regression between soil C or N sequestration in all the sites of land use change and the year of cropland abandonment. The dotted lines indicate $y = 0$. The values represent the means ± SE. * Significance at $P < 0.05$, ** significance at $P < 0.01$, *** significance at $P < 0.001$ and ns indicates non-significance ($P > 0.05$). $n = 95$.

Soil C and N sequestration in different soil layers exhibited similar characteristics. They both increased with years since farmland conversion (Fig. 4). However, soil C and N stocks have different sequestration rates in different soil layers following farmland conversion (Fig. 4). Soil C sequestration significantly increased in all four layers of the 0–50 cm soil with years since farmland conversion ($P < 0.05$; Fig. 4A–D), but soil N sequestration significantly increased only in the 0–20-cm soil following farmland conversion ($P < 0.01$; Fig. 4F and G). The remaining soil layers did not exhibit significant increases over time ($P > 0.05$; Fig. 4E, H–J).

3.3. Relationship between soil C and N sequestration

Soil C and N sequestration showed significant positive correlations ($P < 0.001$; Fig. 5). The value of soil C sequestration was approximately 8–10 times that of soil N sequestration following

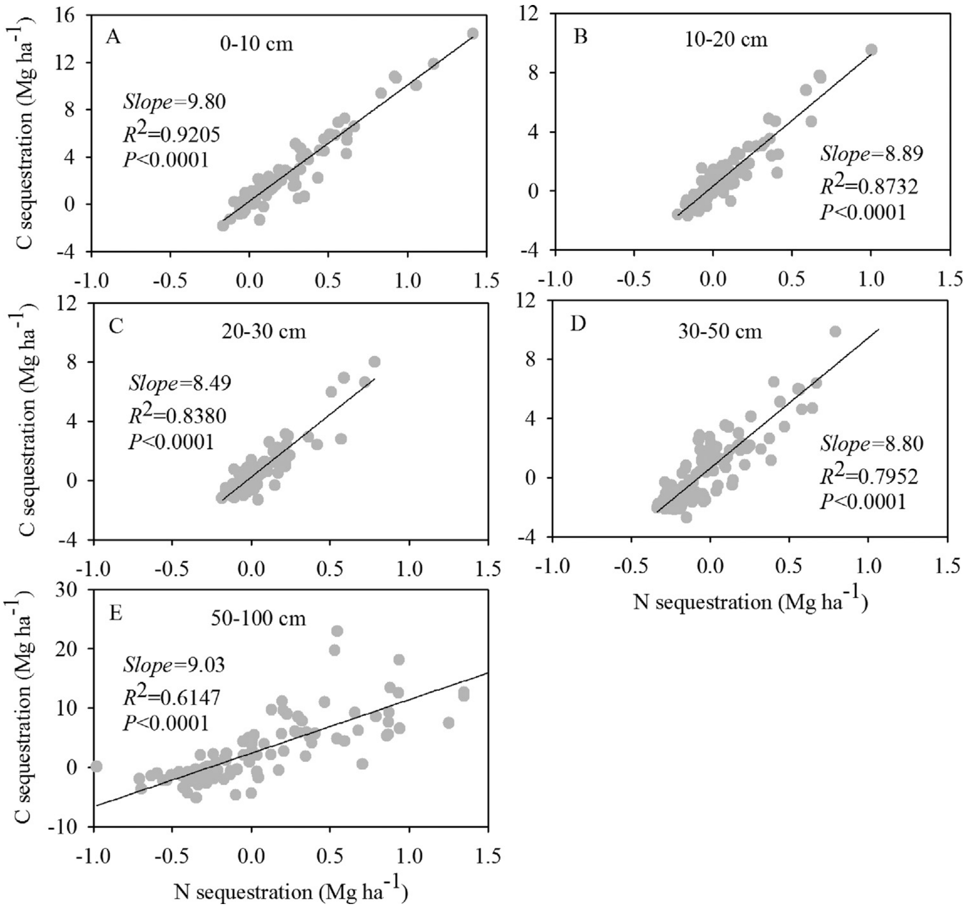

Fig. 5. Relationship of soil C and N sequestrations, and both soil C and N sequestration rates after cropland abandonment in each soil depths. Note: The values represent the means in each site of different land use types. Significance was evaluated at the 0.05 level ($P < 0.05$).

cropland abandonment (Fig. 5). Correlations between soil C sequestration and soil N sequestration were stronger in the more shallow soils and weaker in the deeper soil layers; the strength of the correlations also declined as soil depth increased (Fig. 5). In addition, soil C and N sequestration showed significant positive correlations, which were greater in surface soil layers than in deeper layers (Fig. 5).

4. Discussion

Soil C and N varies based on the type of land use, and these variations are highly complex (Zhang et al., 2013b). In our study, we found that land-use types had significant effects on soil C and N sequestration (Table 1, Figs. 2 and 3). Soils with different vegetations have different litter decomposition processes leading to the difference in release of C and N to soil (Zhang et al., 2013b). Prietzel and Bachmaan (2012) have reported that tree species with different plant traits and stand properties can impact on retentions of soil organic C and N, for instance, influence on releasing nutrients to soil via mineralization (Mueller et al., 2012). In addition, restoration age had also significant effect on soil C and N sequestration (Table 1). The OL and MG had the higher soil C and N sequestrations than other three types of NG, WL and SL in the early stage (0–10 years) since cropland abandonment (Figs. 2 and 3), this maybe because OL and MG was influenced by fertilization of with inorganic fertilizer (urea) and organic fertilizers (goat manure). Moreover, in the later stage since cropland abandonment (>20 years), the SL had the higher soil C and N sequestrations than the WL and NG (Figs. 2 and 3). The results suggested that to get long-term (>20 years) soil C and N sequestration benefits, planting shrub is a better restoration type in the transition from forest to grassland than natural grassland and woodland in the center of Loess Plateau where the annual rainfall is close to 500 mm.

In our study, restoration ages also had positive significant effect on soil C and N sequestration after cropland abandonment (Fig. 4), especially after cropland was converted to the natural grassland, woodland and shrubland (NG, WL and SL; Table 2). Although the mechanisms that control the accumulation rates following cropland abandonment are different for C and N (McLauchlan, 2006), similar temporal patterns in soil C and N stock changes following cropland abandonment have been observed by a number of field studies (Morris et al., 2007; Deng et al., 2013). Zeng et al. (2007) have found that a cropland converted into grassland exhibited increased SOC and STN and increased fractions of soil components and total soil porosity, leading to soil bulk density (BD) decreases along with the vegetation restoration and revegetation process after cropland abandonment. Additionally, we also found that SOC and STN were significantly negatively correlated with BD (Fig. 6). In addition, in our study, we used the "space" for "time" method to study soil C and N sequestration change over time; although useful, this approach has an important limitation, which is site variability. Bartuska and Frouz (2015) showed that the chronosequence approach combined with repeated measures provides a good method to overcome the problem caused by the initial heterogeneity. However, the average increases in C stock were similar as determined by the chronosequence and real-time approaches (Bartuska and Frouz, 2015). Therefore, the chronosequence approach is a powerful tool because

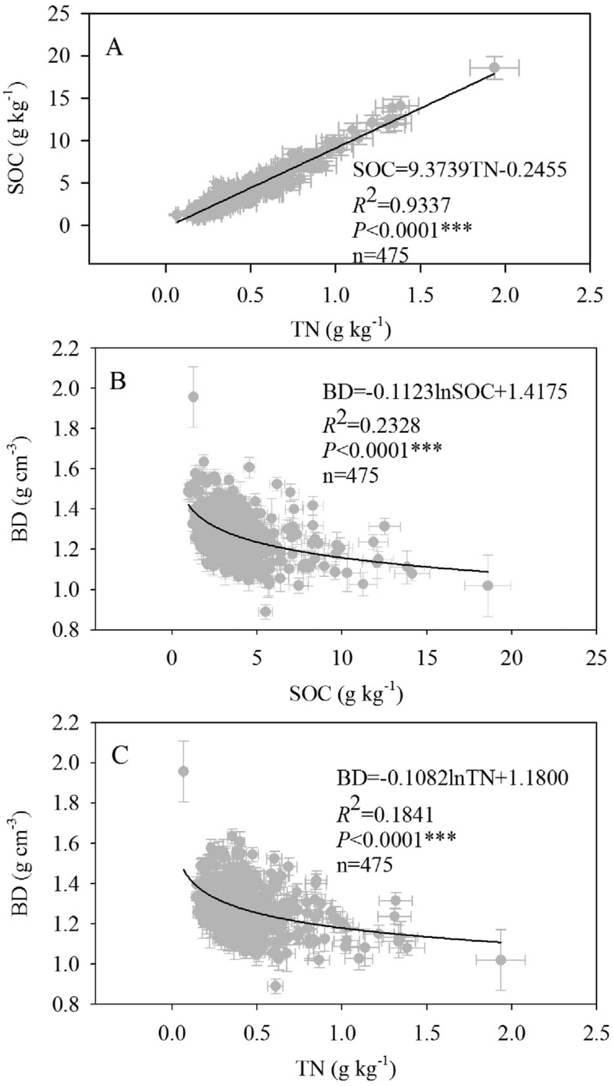

Fig. 6. Relationship between soil organic carbon (SOC) and soil total nitrogen (STN), soil bulk density (BD) and SOC, and BD and STN in all whole soil layers of 0–100 cm soil. Note: The values represent the means ± SE. *** Significance at $P < 0.001$.

it enables researchers to investigate processes that are difficult or impossible to investigate in real time because they occur over decades.

Soil physico-chemical properties differed among soil depths (Ritter, 2007; Li et al., 2012; Deng et al., 2014; Wang et al., 2014). In our study, soil C and N sequestrations at different soil depths both increased with age in NG, WL and SL (Table 2). In addition, similar to the findings of the study, land-use-conversion-induced changes in soil C and N at different soil depths have been demonstrated previously for various soil properties. For example, Wang et al. (2014) found that SOC increased in topsoil but decreased in deeper soils with time. In northeast China, Wang et al. (2011a,b) found that slight N increases in topsoil but a marked N decreases in subsoil (20–60 cm). Our results for the Loess Plateau were consistent with this finding (Figs. 2 and 3). Jobbágy and Jackson (2000) have reported that soil C dynamic in soil profile was closely related to the relative depth distribution of plant allocation between shallow and deep roots. These features may also affect soil N due to its close correlation with soil C (Figs. 5 and 6). Generally, if soil C sequestration is not accompanied by a simultaneous N gain, the ecosystem will become increasingly N limitation (Luo et al., 2004). The present study showed that there had a strong correlation between C and N sequestration changes following vegetation restoration and revegetation process after cropland abandonment (Fig. 5), and soil C and N stock tended to increase linearly with age, especially in the top 20-cm soils (Fig. 4). The increase in N stock will reduce N limitation and support long-term C sequestration, but we also found that soil C and N stocks have different sequestrations in different soil depths (Figs. 2 and 3), indicating that soil C and N sequestration mechanisms are varied in the soil profile. In the 20–50-cm soil depths, soil C sequestration had significantly increased with age but not soil N sequestration, which suggested that the subsoil may have the occurrence of increasing N limitation after long-term vegetation restoration/revegetation, and then reducing the rate of C sequestration.

Many studies have documented that soil C and N have significant positive correlations (Li et al., 2012; Deng et al., 2013). In our study, we also observed this trend (Fig. 5). Deng et al. (2013) reported that soil C stock was approximately 10 times of soil N stock over 30 years after cropland was converted into grassland on the Loess Plateau. We also found the value of soil C sequestration to be approximately 8–10 times that of soil N sequestration following cropland abandonment (Fig. 5). Moreover, the correlation between soil C sequestration and soil N sequestration was stronger in topsoils and weaker in deeper soil layers, and it declined as soil depth increased (Fig. 5). One potential mechanism explaining this result is that topsoils accumulate more C and N than deeper soil layers. Moreover, rainfall may facilitate the migration of N into deeper soils, thereby increasing N accumulation in the subsoil during vegetation restoration and revegetation process, and decreased soil C–N relations.

5. Conclusions

Both age and land-use change types had a significant effect on soil C and N sequestration. After cropland abandonment, soil C and N sequestration increased with restoration age especially after cropland was converted to the natural grassland, woodland and shrubland. In light of this finding, it is clear that restored soil can play an extensive role in carbon and nitrogen sink efforts. Our results also suggested that soil C and N stocks have different sequestrations in different soil depths and the subsoil may have the occurrence of progressive N limitation during the long-term vegetation restoration/revegetation process. In addition, our study suggests that to get long-term (>20 years) soil C and N sequestration benefits, the shrub is a better restoration types in the transition from forest to grassland than natural grassland and woodland on the middle of Loess Plateau with the annual rainfall of 500 mm, and orchard and man-made grassland (alfalfa) due to too much of human management also have a good soil C and N sequestration benefits in the short time (<20 years). Therefore, from the perspective of soil C and N management, Planners should take into account the vegetation type or land cover when making vegetation restoration and revegetation policy.

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