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Synchronous sequestration of organic carbon and nitrogen in mineral soils after conversion agricultural land to forest

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ABSTRACT

Agricultural land-use change is a global issue with significant implications for global warming and ecosystem functionality. Uncertainty regarding carbon (C) and nitrogen (N) sequestration and their dynamics after land-use change hampers an accurate understanding of the C and N cycles. To address the influence of converting agricultural land to forest on organic carbon (OC) and N sequestration and their coupling relationships, we collected topsoil (0 − 10 cm depth) and subsurface soil (10 − 20 cm depth) in afforested woodlands 10, 20, and 35 yrs after the establishment of *Robinia pseudoacacia* in abandoned farmlands on the Loess Plateau, China. We analyzed the concentrations and stocks of OC and N in bulk soils and water-stable aggregates. We found that afforestation of farmland resulted in a relative increase of 30 % in the proportion of macroaggregates (8 – 0.25 mm) but a relative decrease of 45 % and 30 % in the proportions of microaggregates (0.25 - 0.053 mm) and silt + clay (< 0.053 mm), respectively. The respective OC and N stocks increased by 87 % and 74 % in bulk soils and by 278 % and 159 % in macroaggregates after 35 yrs of afforestation. Macroaggregates accounted for 69 % and 68 % of the OC and N stocks, respectively, in bulk soils at the 0 – 20 cm depth. However, the OC and N stocks in microaggregates and silt + clay were only slightly affected. These results indicated that the conversion of agricultural land to forest could sequester OC and N in both bulk soils and aggregates, mainly macroaggregates. In addition, the dynamics of OC and N were significantly correlated, implying synchronous OC and N sequestration in soils after converting agricultural land to forest.

1. Introduction

Over the last few decades, the carbon (C)–nitrogen (N) biogeochemical cycles in terrestrial ecosystems have attracted increasing worldwide attention, mostly due to their impacts on global warming and ecosystem functionality (Davidson et al., 2007). However, large-scale changes in land use have dramatically influenced the capacity of the agricultural ecosystem to sequester C and N (Serge-Pacôme et al., 2017; Yan et al., 2018) as well as the emissions of greenhouse gases. Globally, soil lost 40 − 90 Pg C and released 1.6 ± 0.8 Pg C to the atmosphere every year in the 1990s due to agricultural cultivation and other disturbances (Smith, 2008). In China, cultivation of soils leads to a decrease in OC at an average rate of 15 t C ha^{-1}, and the overall C stock in the topsoil (approximately 30 cm) decreases by 2 Pg every year (Fu et al., 2010; Song et al., 2005). Converting natural ecosystems to agricultural ecosystems results in a 20–59 % decrease in the soil C stock (Birch-Thomsen et al., 2007; Kopittke et al., 2017; Murty et al., 2002; Wainkwa Chia et al., 2017) and a 15–42 % decrease in soil N stock (Murty et al., 2002; Kopittke et al., 2017; Wainkwa Chia et al., 2017). In contrast to this land-use change, afforestation on agricultural land is an effective approach to sequester OC and N in soils and ecosystems due to less disturbance, more organic matter inputs, and lower decomposition (Guo and Gifford, 2002; Lemenih et al., 2005). For example, Guo and Gifford (2002) reported 53 % increases in soil OC stock, and Lemenih et al. (2005) reported 13 % and 19 % increases in soil OC and N stocks after converting farmland to secondary forest. However, no changes (Li et al., 2012; Wainkwa Chia et al., 2017) or a net loss of OC and N from soils (Kirschbaum et al., 2008) was observed after afforestation of cropland. Such inconsistency might be related to the difference in time since land-use conversion, therefore, it is essential to go on step further to study the dynamic trend of soil C and N sequestration after the conversion of agricultural land to forest.

The conversion of land use not only affects the quantity of soil OC and N but also influences the distribution of OC and N among aggregate

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size class. The results from Qiu et al. (2015) showed that converting farmland to forest on the Loess Plateau of China could result in the aggregation of soil particles, drive the accumulation of OC in aggregates. Given that soil aggregates physically protect soil OC from decomposition by microbes (Liu et al., 2020; Razafimbelo et al., 2008), the accumulation of OC in aggregates might accelerate OC sequestration in agricultural land and further mitigate potential increases in atmospheric greenhouse gases (Poeplau et al., 2011). However, the dynamics of N in aggregates following afforestation have rarely been addressed, which hinders understanding of the role of N on soil C sequestration.

The C—N coupled relationships are significant in stressing the long-term sustainability of C and N sequestration in terrestrial ecosystems (Li et al., 2012; Luo et al., 2004). Generally, N availability controls C sequestration in afforested soils (Liang et al., 2014) or abandoned agricultural soils (Knops and Tilman, 2000). For example, the results from Liang et al. (2014) showed that N availability limited the sustainability of C sequestration in afforested soils owing to the coupled cycling of C and N, especially with an increase in atmospheric carbon dioxide (CO_2) concentration. Melillo et al. (2011) found that increased soil inorganic N resulted in marked accumulation of the soil C stock in a deciduous forest, New England. Deng et al. (2014c) reported that an increase in soil C stocks would be limited due to decreased soil N availability on a long-term scale. These previous studies suggest that biologically available N regulates C sequestration in terrestrial ecosystems due to their coupled relationship. Although scientists have addressed the changes in soil C and N sequestration and their influential factors after land-use conversion (Baddeley et al., 2017; Don et al., 2011), the dynamic relationship between C and N after land-use conversion is still worth studying and is essential for the estimation of the C and N sequestration potential in agricultural ecosystems.

In this study, we aimed to quantify the effects of land-use conversion from abandoned farmland to black locust (*R. pseudoacacia*) stands aged 10, 20, or 35 yrs on the concentrations and stocks of OC and N in bulk soils and aggregates on the Loess Plateau, China. We also aimed to assess the relationship between OC and N and to examine how this relationship varied among aggregates. We hypothesized that (1) OC and N would be sequestered in bulk soils and aggregates, especially macroaggregates, after the conversion of agricultural land to forest and (2) OC and N sequestration would be synchronous regardless of the aggregate fraction and afforestation age after land-use change, due to their coupled cycling in most soils.

2. Materials and methods

2.1. Experimental site description

We conducted our experiments in Yongshou County (N34°49′ - N34°51′, E108°10′ - 108°12′), Shaanxi Province, in the southern part of the Loess Plateau, China. The study site has a warm temperate continental climate, with dry and cold winters and rainy and hot summers. The mean annual temperature and rainfall are 10.8 °C and 602 mm, respectively. According to the FAO (2015), the soil type in this area is an Anthrosol, with a loamy clay texture.

Before conversion, the land use type at our study site was farmland, which suffered severe soil erosion and land degradation due to extensive agricultural production (Zhang et al., 2018). The main planting system was winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.) rotation. Chemical fertilizer was applied at rates of 287 (± 63) kg N $ha^{-1}y^{-1}$and 104 (± 16) kg P $ha^{-1}y^{-1}$ to the farmland. Manure fertilizer has not been used on the farmland for the last two decades. Fertilizer N applied at this rate did not result in the accumulation of N in the soil according to a previous study in the same region (Zhang et al., 2018). To prevent soils from degrading, many farmlands were abandoned and converted to forests (afforestation). Today, Yongshou County covers 17,333 ha of forestland, and the forest coverage has reached 89 %. The major forest species in the afforested land are black locust (*R. pseudoacacia*), Chinese pine (*Pinus tabuliformis* Carr.), Liaodong oak (*Quercus liaotungensis Koidz.*) and birch (*Betula platyphylla Suk.*), of which black locust accounts for 15,000 ha. Following afforestation, all species were monocultures with natural growth. These forestry resources were protected and developed by the state and local forestry administrations. Our study only considered the first rotation forest (all forests after afforestation that grew naturally).

2.2. Field investigation and sampling

To study soil OC and N sequestration and their dynamic relationship after converting agricultural land to forest, we selected an abandoned farmland and three afforested areas that were converted from abandoned farmland 10, 20, or 35 yrs ago to compose a chronosequence. A chronosequence is composed of a range of sample sites spread out over time to study the temporal variation in soil development at multiple time scales. The basis of this method is that each site in the sequence has similar natural and historical conditions, differing only in age (Walker et al., 2010). The area of each forest was 5 ha, and there was approximately 1 − 3 km between each site. The dominant plants in the forests were black locust. All stand ages of forests were determined by drilling technology.

In September 2014, we established 3 plots (10 m × 10 m) less than 40 m apart that had similar natural and geographical conditions in the farmland and the afforested areas with three afforestation ages (i.e., 10, 20, and 35 yrs) for field investigation and soil sampling (Fig. 1). The main forest and farmland information was shown in Table 1. In general, there was an organic layer consisting of plant residues in various stages of decomposition in the afforested areas that contained large fractions of C and N (De Marco et al., 2013). However, there was no organic layer in the farmland. Therefore, to ensure the samples were comparable, the organic layer was not included in this study. Before sampling, we removed the litter and organic matter from our afforested plots.

To measure soil bulk density (BD), we collected 3 replicated samples from each soil layer (0–10, 10 − 20 cm depth) in each plot using a stainless-steel ring cutter (5-cm diameter × 5-cm height). Seven additional soil samples from each soil layer of the plot were also randomly collected from depths of 0–10 and 10 − 20 cm to constitute a composite sample (ca. 1 kg). A total of 24 soil samples (4 land use types × 3 plots × 2 soil depths) were collected. Each sample was placed in a tin box or an aluminium box to maintain the original structure of the soil. All soil samples were protected from vibration or tipping during loading and transportation. When returned to the laboratory, all undisturbed soil samples were gently stripped into small clods with a diameter of 10 − 12 mm along the natural structure. Visible organic material and small stones were moved. The wet soil samples were naturally dried and preserved at room temperature to analyze soil aggregation fractions and OC and N.

2.3. Laboratory analysis

The soil BD was determined based on the original volume and dry mass (dried at 105 °C) of each soil core using the soil bulk sampler method (Jia et al., 2005). The aggregates were separated into 3 fractions, macroaggregates (8 - 0.25 mm, MA), microaggregates (0.25 - 0.053 mm, MI), and silt + clay (< 0.053 mm, SC), with the wet-sieving method (Cambardella and Elliott, 1993). In this method, a 100 g soil sample was placed on the top of a nest of sieves with opening sizes of 0.25 and 0.053 mm arranged from top to bottom. Wet sieving was performed on the distilled water using a shaker for 5 min at a frequency of 50 times every two minutes. After wet sieving, soils remaining on each sieve were collected separately and were dried to constant weight at 40 °C. The bulk soil and aggregate samples were passed through 0.25-mm sieves to analyze the OC concentration with the Walkley–Black method and the N concentration with the Kjeldahl method (Page et al.,

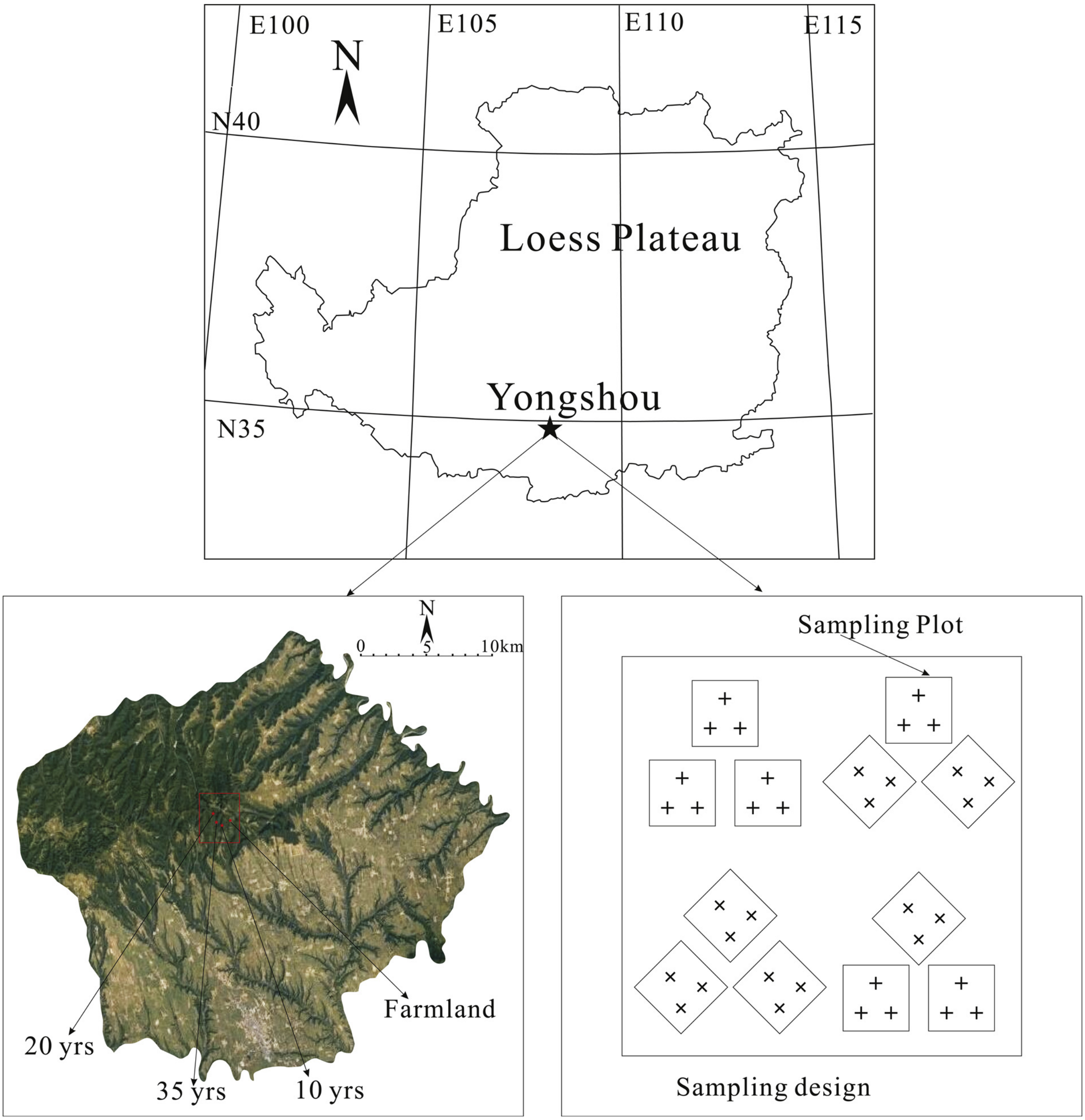

Fig. 1. The location of the study site and diagram of sampling design.

1982).

The OC and N stocks (kg m^{-2}) in the bulk soils were calculated as follows:

$$\text{OC stock} = \frac{D \times BD \times OC}{100}$$

$$\text{N stock} = \frac{D \times BD \times N}{100}$$

where D is the soil depth (cm), BD is the soil bulk density (g cm^{-3}), and OC and N are the respective soil OC and N concentrations (g kg^{-1}) of the 0–10 or 10 − 20 cm soil depth.

The OC and N stocks (kg m^{-2}) in aggregates were calculated as follows:

Table 1
The basic information of the study sites on the Loess Plateau, China.

Land uses	Longitude	Latitude	Elevation (m)	Slope degree	DBH (cm)	Height (m)	Sand (%)	Silt (%)	Clay (%)	pH	OC (g kg^{-1})	N (g kg^{-1})
Farmland	108.12°	34.84°	1402	4°	NA	NA	29.88	42.32	27.80	6.86	8.81	0.87
10 yrs Black locust forest	108.10°	34.84°	1398	4°	12.5	13.0	34.49	39.15	26.36	8.23	11.87	1.26
20 yrs Black locust forest	108.11°	34.84°	1386	5°	14.2	14.6	32.91	38.88	28.21	7.40	17.14	1.66
35 yrs Black locust forest	108.12°	34.84°	1405	5°	23.0	15.4	30.70	40.44	28.85	7.09	19.08	1.78

DBH: Diameter at breast height of the tree; Height: the height of tree. BD: the soil bulk density; OC: soil organic carbon concentration; N: soil total nitrogen concentration.

$OC_i\ stock = M_i \times OC_i$

N_i stock= $M_i \times N_i$

$$M_i = \frac{D \times BD \times W_i}{100}$$

where *i* is the *i*th fraction of the aggregate (MA, MI, and SC), M_i is the mass of the *i*th aggregate (kg m^{-2}), OC_i and N_i represent the OC and N concentration, respectively, in the *i*th fraction (g kg^{-1} aggregates), and W_i is the proportion of the *i*th aggregate (%).

We calculated the differences in parameters between abandoned farmland (control) and afforested land with various stand ages to assess the absolute and relative changes in these parameters. The MRT is used to reflect the inputs and decomposition balance of OC or N in soil (Qiu et al., 2015), which is defined as the average residence time (Fröberg et al., 2011). Soil OC and N dynamics along the afforestation chronosequence conformed to the commonly used first-order model (Six and Jastrow, 2002) in our study:

$$OC(t) = OC_e - (OC_e - OC_0) \times e^{-kt}$$

$$N(t) = N_e - (N_e - N_0) \times e^{-k't}$$

where t is the afforestation time (yrs), OC_e and N_e are the respective OC and N concentrations (g kg^{-1}) when the soil reaches a new steady state, OC_0 and N_0 are the initial OC and N concentrations (g kg^{-1}), respectively, before afforestation, *k* is the turnover rate constant (yr^{-1}), OC(t) and N(t) are the respective soil OC and N concentrations in forests aged (t) 10, 20, and 35 yrs and in the abandoned farmland (t = 0). The parameters (OC_0, OC_e and *k*; N_0, N_e and *k*) were obtained by using these data to fit the first-order model. The exponential model with 3 parameters was used to fit the model in SigmaPlot software (version 12.5, SYSTAT, USA).

The MRT was calculated as follows:

$$MRT = \frac{1}{k}$$

The overall input rate (*I*) of OC or N during 35 years of afforestation was calculated as:

$$I(OC) = OC_e \times k$$

$$I(N) = N_e \times k$$

2.4. Statistical analysis

First, we tested the data for normality and homogeneity of variance. Then, we used two-way ANOVA to determine the effects of afforestation and soil depth and their interaction on the soil BD, aggregates, OC, N, and C:N ratio in all soils. Furthermore, we analyzed the effects of afforestation age on all parameters at the different soil depths by post hoc tests and established a correlation between OC-related parameters and N-related parameters by regression analysis in either bulk soils or aggregates. All statistical analyses were carried out using SPSS (version 20.0, IBM, SPSS, USA).

3. Results

3.1. BD and the distribution of water-stable aggregates

In our study, soil BD was significantly affected by afforestation and soil depth ($P = 0.001$, Table 2) and showed a decreasing trend after the change from agricultural land to forest (Fig. 2). Moreover, the decrease in BD in the topsoil (0 − 10 cm depth) was faster than that in the subsurface soil (10 − 20 cm depth). When averaged across all sites, afforestation resulted in BD decreases of 0.45 % per year in the topsoil and of 0.29 % per year in the subsurface soil.

The proportion of aggregates was affected by afforestation and soil depth and their interaction (Table 2). In general, the proportion of the MA fraction increased after the land-use change from agricultural land to forest, but the MI and SC fractions showed the opposite trend (Fig. 3). The changes in aggregate proportion were greater in the topsoil than in the subsurface soil ($P < 0.01$). MA increased by 1.24 % yr^{-1} and 0.45 % yr^{-1}, MI decreased by 1.78 % yr^{-1} and 0.81 % yr^{-1}, and SC decreased by 1.57 % yr^{-1} and 0.14 % yr^{-1} in the top and subsurface soils, respectively. Furthermore, the mass proportion of each aggregate fraction changed rapidly in the first 20 yrs of conversion across the whole soil depth. As shown in Fig. 3, the mass proportion of MA increased by 32.3 % and 15.8 % during the first 20 yrs of conversion at the two soil depths, and the mass proportion of MI increased by 8.5 % in the topsoil and changed little in the subsurface soil during the last 15 yrs of afforestation (the period between 20–35 yrs of afforestation).

Table 2
Results of two-way analysis of variance (F and P) for the effects of afforestation and soil depth on soil bulk density (BD), proportion of each aggregate size fraction, concentrations of organic carbon (OC) and nitrogen (N), the C:N ratio, and stocks of OC and N in bulk soils and aggregates.

Soil metrics	Soil Depth		Afforestation		Afforestation × Soil depth	
	F	P	F	P	F	P
BD	9.66	**0.001**	17.52	**0.001**	3.10	0.056
MA proportion	251.51	< **0.001**	68.16	< **0.001**	13.95	< **0.001**
MI proportion	45.68	< **0.001**	42.11	< **0.001**	4.21	< **0.001**
SC proportion	125.41	< **0.001**	22.78	< **0.001**	6.83	< **0.001**
OC in BS	222.56	< **0.001**	62.86	< **0.001**	46.01	< **0.001**
N in BS	126.41	< **0.001**	35.24	< **0.001**	21.74	< **0.001**
OC in MA	453.03	< **0.001**	197.35	< **0.001**	94.71	< **0.001**
OC in MI	179.69	< **0.001**	45.56	< **0.001**	32.47	< **0.001**
OC in SC	205.60	< **0.001**	49.36	< **0.001**	38.47	< **0.001**
N in MA	507.76	< **0.001**	165.58	< **0.001**	89.57	< **0.001**
N in MI	150.81	< **0.001**	38.48	< **0.001**	24.30	< **0.001**
N in SC	87.60	< **0.001**	26.31	< **0.001**	15.68	< **0.001**
OC stock in BS	78.48	< **0.001**	21.83	< **0.001**	19.15	< **0.001**
N stock in BS	98.65	< **0.001**	28.14	< **0.001**	23.27	< **0.001**
OC stock in MA	516.36	< **0.001**	203.63	< **0.001**	105.43	< **0.001**
OC stock in MI	40.41	< **0.001**	6.28	**0.005**	11.53	< **0.001**
OC stock in SC	11.35	**0.004**	13.07	< **0.001**	0.28	0.839
N stock in MA	551.68	< **0.001**	164.75	< **0.001**	90.76	< **0.001**
N stock in MI	20.18	< **0.001**	1.61	0.226	6.01	**0.006**
N stock in SC	23.78	< **0.001**	15.19	< **0.001**	0.79	0.517
C:N in BS	2.24	0.154	2.45	0.101	2.53	0.094
C:N in MA	6.18	**0.024**	27.50	< **0.001**	3.54	**0.039**
C:N in MI	39.76	< **0.001**	13.23	< **0.001**	13.91	< **0.001**
C:N in SC	12.46	**0.003**	1.41	0.276	2.28	0.119

BS: bulk soils; MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm). Bold values were significant at $P < 0.05$.

3.2. Changes in OC and N in bulk soils

The soil depth and afforestation and their interaction significantly affected OC and N in the bulk soils ($P < 0.001$, Fig. 2, Table 2). In general, OC and N increased markedly after the conversion of agricultural land to forest and presented to a linear trend with afforestation age; these increases were greater in the topsoil than in the subsurface soil (Fig. 2). The respective OC and N concentrations increased by 0.63 and 0.06 g kg^{-1} yr^{-1} in the topsoil, and by 0.48 and 0.04 g kg^{-1} yr^{-1} in the subsurface soil after 35 yrs of conversion. Compared to the farmland, the OC stock increased by 0.61, 1.40 and 2.27 kg m^{-2} in the topsoil and by 0.02, 0.19 and 0.04 kg m^{-2} in the subsurface soil after 10, 20 and 35 yrs of afforestation, respectively. Similarly, compared with the farmland, the N stock in the afforested soil increased by 0.06, 0.12 and 0.19 kg m^{-2} in the topsoil and by 0.03, 0.03 and 0.02 kg m^{-2} in the subsurface soil after 10, 20 and 30 yrs, respectively.

The turnover rate constant (*k*) and overall input rate (*I*) of OC and N predicted by the first-order model were greater for the topsoil than for

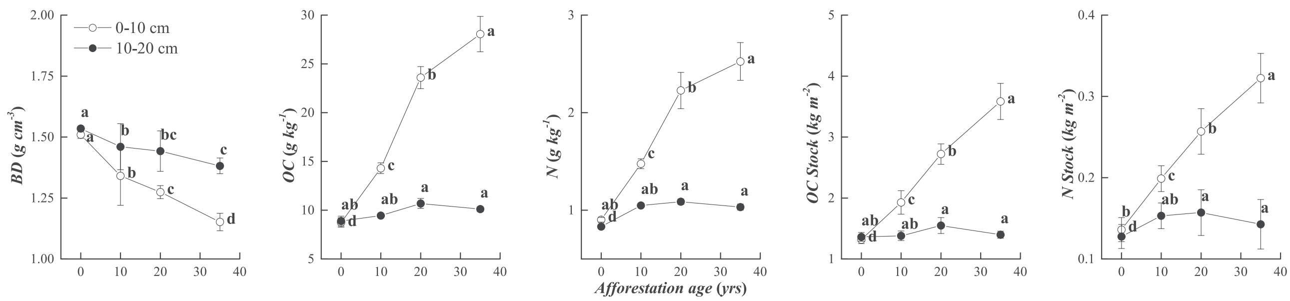

Fig. 2. Changes in soil bulk density (BD), organic carbon (OC) and nitrogen (N) concentration and stock in bulk soils at 0-10 and 10-20 cm depths after the conversion of agricultural land to forest on the southern Loess Plateau. Means with the same lowercase letters within the same soil depth are not significantly different at $P < 0.05$ among afforestation ages. Error bars are two standard errors of the means.

the subsurface soil (Table 3). The simulation showed that the respective k and I values of OC for bulk soils were 0.10 yr^{-1} and 1.97 g kg^{-1} yr^{-1} in the topsoil and 0.01 yr^{-1} and 0.05 g kg^{-1} yr^{-1} in the subsurface soil. The respective k and I values of N for bulk soils were 0.11 yr^{-1} and 0.19 g kg^{-1} yr^{-1}in the topsoil, and 0.04 yr^{-1} and 0.01 g kg^{-1} yr^{-1} in the subsurface soil. Accordingly, the MRT (i.e., $1/k$) of OC and N was shorter in the topsoil (11 and 9 yrs, respectively) than in the subsurface soil (125 and 24 yrs, respectively).

3.3. Changes in OC and N in water-stable aggregates

The OC and N varied greatly with aggregate size ($P < 0.001$), and were affected by the direct and indirect effects of soil depth and afforestation in each aggregate (Fig. 3, Table 2). In general, higher OC and N were discovered in MA and MI than in fine particles (e.g., SC) in both soil layers. Furthermore, the OC and N in a given aggregate, particularly MA and MI, were higher in the topsoil than in the subsurface soil (Fig. 3).

Additionally, OC and N concentrations increased significantly with the afforestation age in each aggregate. These increases were larger in topsoils than in subsurface soils, and marked increases occurred during the first 20 yrs of afforestation (Fig. 3). Compared to the farmland, the OC concentrations in the respective MA, MI, and SC fraction increased by 27.68, 32.91, and 7.18 g kg^{-1} in the topsoil and by 5.40, 4.14, and 1.06 g kg^{-1} in the subsurface soil after 20 yrs of afforestation. Similarly, the N concentrations in the respective MA, MI and SC fractions increased by 2.13, 2.58, and 0.67 g kg^{-1} in the topsoil and by 0.38, 0.42, and 0.13 g kg^{-1} in the subsurface soil after 20 yrs of afforestation.

Similar to the OC and N concentrations, the aggregate-associated stocks were also affected by the direct and indirect effects of soil depth and afforestation (Table 2). The OC and N stocks in the MA showed marked increases after land-use change but changed little in the MI and SC at the two soil depths (Fig. 3). The MA-OC stock increased by 3.01 and 0.23 kg m^{-2}, and the MA-N stock increased by 0.23 and 0.03 kg m^{-2} in topsoil and subsurface soil, respectively, after 35 yrs of afforestation. Specifically, throughout the whole soil, the MA contributed most of the OC and N. For example, the MA-OC stock accounted for 75 % and 63 % of the OC stock in the bulk soils, and the MA-N stock accounted for 75 % and 61 % of the N stock in the bulk soils at the two soil depths, respectively (Table 4). Moreover, the changes in the MA-OC stock accounted for 97 % and 121 % of the OC stock changes in the bulk soils in the topsoil and subsurface soil, respectively. The changes in the MA-N stock accounted for 100 % and 123 % of the N stock changes in the bulk soils in the topsoil and subsurface soil, respectively.

The k and I values of the OC and N for aggregates were greater while the MRTs were shorter in the topsoil than in the subsurface soil (Table 3). The k and I values of the OC and N in the two soil layers increased with aggregate size, following the order MA > MI > SC (Table 3). Accordingly, the longest MRTs of OC and N were found in the SC fraction in the two soil layers.

3.4. Correlation between OC and N

Our results showed that the C:N ratio in the bulk soils was not affected while that in MA and MI was markedly affected by afforestation, soil depth and their interaction (Table 2). Overall, C:N ratio ranged from 7 to 12 for all the soil samples in this study. Generally, C:N ratio increased with afforestation age in the topsoil but showed different changes with afforestation age in the subsurface soil. For example, the C:N ratio in the subsurface soil increased from 8.56 ± 0.76 in the farmland to 10.29 ± 0.18 for MA but was comparatively stable for MI and SC with afforestation age (Fig. 4).

In addition, the results also proved that the accumulation of OC and N was synchronous after land-use change, regardless of the aggregate fraction and afforestation age (Table 5). For example, significant positive correlations were found between OC and N concentrations, between OC and N stocks, between the overall input rates of OC and N, and between the turnover rate constants of OC and N ($P < 0.001$) across all soil depths and afforestation ages. Moreover, a significant positive correlation was also observed between the absolute changes in OC and N and between the relative changes in OC and N after afforestation when examined across all soil depths and afforestation ages ($P < 0.0001$).

4. Discussion

Examining soil OC and N dynamics and their coupled relationship in bulk soils and water-stable aggregates after the conversion of agricultural land to forest will help in understanding the soil C and N pools and cycles in ecosystems. Our results indicated that the conversion of agricultural land to forest resulted in soil OC and N sequestration, mainly in MA, supporting our first hypothesis. We further illustrated that OC and N sequestration was synchronous regardless of aggregate fraction and afforestation age, verifying our second hypothesis. These results highlighted the coupled cycles of soil OC and N and the great potential of afforestation in sequestering OC and N and thus mitigating greenhouse gas emissions.

4.1. OC and N sequestration in bulk soils

The conversion of agricultural land to forest resulted in OC and N sequestration in the bulk soils in our study (Fig. 2), which is consistent with previous studies in various regions (Baddeley et al., 2017; Guo and Gifford, 2002; Lemenih et al., 2005; Zhang et al., 2018). This sequestration was mainly due to the greater input of organic matter from both above- and belowground biomass (Markewitz et al., 2002) and the higher abundance and diversity of microbial communities (Chavarria et al., 2018; Li et al., 2018). In addition, the slower decomposition of organic matter in afforested areas, as indicated by the increased soil C:N ratio (Fig. 4), also contributed to OC and N sequestration after afforestation (Liang et al., 2014). Moreover, compared to agricultural land, forest has no tillage disturbance or fertilizer application (Burst et al.,

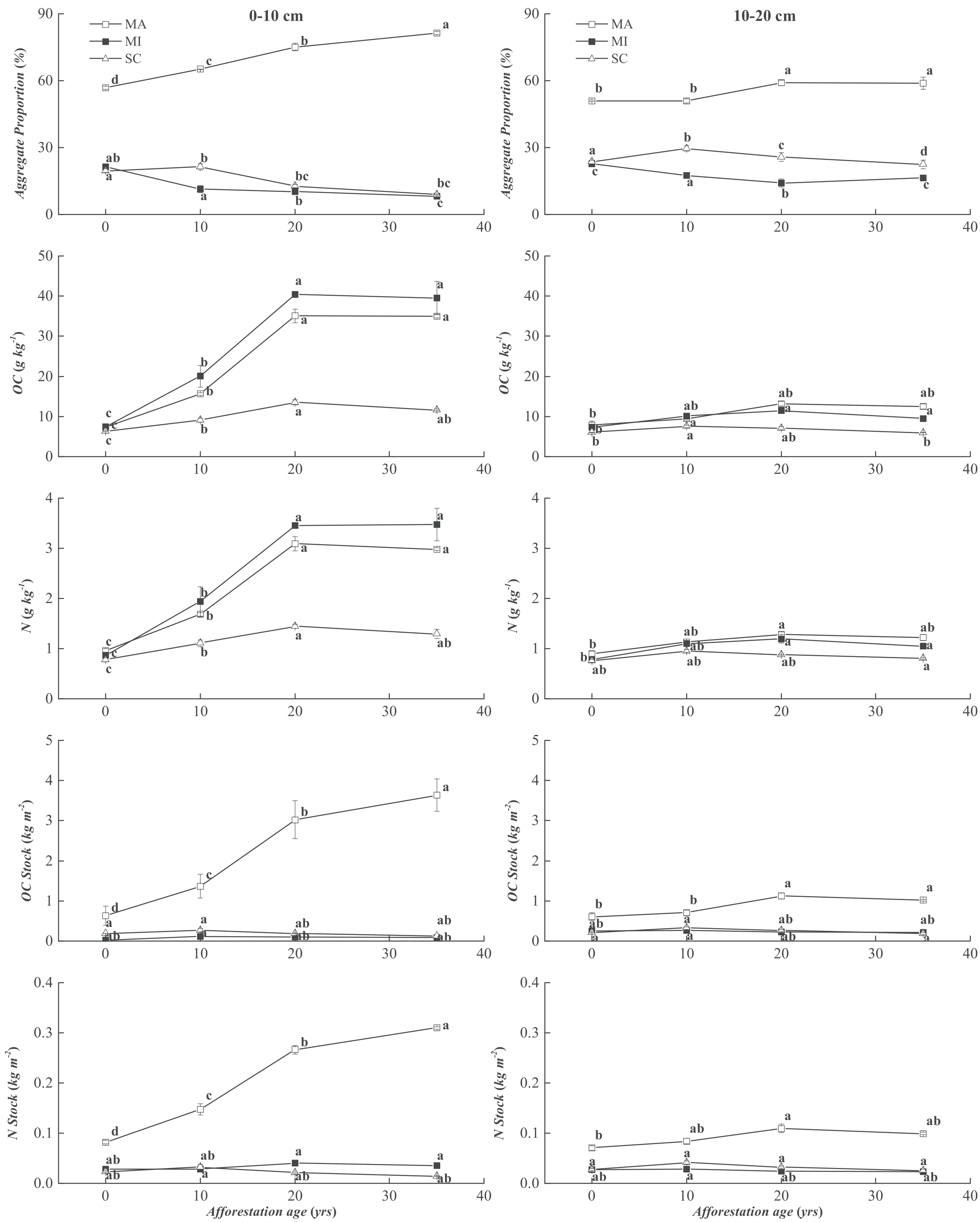

Fig. 3. Dynamics of water-stable aggregates, concentrations and stocks of organic carbon (OC) and nitrogen (N) in each aggregate at the 0-10 cm (Left) and 10-20 cm (Right) depths after the conversion of agricultural land to forest in the southern Loess Plateau. Afforestation age 0 means the farmland. MA: macroaggregates; MI: microaggregates; SC: silt + clay (0.053 mm). Means with the same lowercase letters within the same aggregate fraction are not significantly different at $P < 0.05$ among afforestation ages. Error bars are two standard errors of the means.

2020) but does have increased soil particle aggregation (Fig. 3), which could physically decrease the mineralization loss of OC and N by microbes (Laganière et al., 2010; Yao et al., 2019).

Topsoil sequestered more OC and N than subsurface soil after afforestation of abandoned farmland (Fig. 2), which agrees with the findings of other studies. For example, Wang et al. (2014) found that soil organic matter accumulated 262.1 mg kg^{-1} yr^{-1} in the topsoil (0 − 20 cm) but decreased 36.2–123.9 mg kg^{-1} yr^{-1} in deeper soils (20 − 80 cm) after long-term larch plantations established in northeastern China. Deng et al. (2014b) found that afforestation resulted in higher N sequestration in topsoil (0 − 20 cm) than in deeper soil (> 20 cm) in the middle section of the Loess Plateau, China. These results

Table 3
Parameters describing organic carbon (OC) and nitrogen (N) dynamics in bulk soils and aggregates.

Parameters	Soil depth (cm)	OC				N			
		BS	MA	MI	SC	BS	MA	MI	SC
OC or N (g kg^{-1})	0–10	18.67	16.20	3.43	1.58	1.78	1.52	0.31	0.18
	10–20	9.78	5.90	1.70	1.61	1.00	0.62	0.18	0.22
OC_e or N_e (g kg^{-1})	0–10	20.74	28.61	36.42	8.41	1.69	2.17	2.84	0.93
	10–20	6.50	5.65	5.63	48.55	0.30	0.40	0.69	0.30
PI (g kg^{-1})	0–10	39.15	226.45	83.55	10.21	3.41	11.93	7.20	0.84
	10–20	6.21	14.16	5.43	49.00	0.47	0.53	0.56	0.31
k (yr^{-1})	0–10	0.095	0.241	0.133	0.061	0.111	0.211	0.140	0.035
	10–20	0.008	0.133	0.037	0.001	0.042	0.108	0.022	0.033
MRT (yr)	0–10	11	4	8	24	9	5	7	29
	10–20	125	8	27	1000	24	9	15	36
I (g kg^{-1} yr^{-1})	0–10	1.970	6.894	4.552	0.513	0.188	0.458	0.398	0.032
	10–20	0.052	0.752	0.208	0.049	0.013	0.043	0.015	0.010

OC or N: concentration of OC or N when averaged across all afforestation age; OC_e or N_e: concentration of OC or N at a steady state; PI: potential increase of OC or N after afforestation, which was calculated by subtracting OC or N at initial state from OC or N at a steady state; k: turnover rate constant of OC or N; MRT: mean residence time of OC or N; I: overall input rate of OC or N; BS: bulk soils; MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm).

Table 4
The contribution of each aggregate fraction to stocks of organic carbon (OC) and nitrogen (N) in total soils at different afforestation ages and soil depths.

Soil depth (cm)	Afforestation time (yrs)	OC stock			N stock		
		MA (%)	MI (%)	SC (%)	MA (%)	MI (%)	SC (%)
0–10	0	59	23	18	62	21	17
	10	71	15	14	71	14	15
	20	82	13	5	81	12	7
	35	87	10	3	86	10	4
10–20	0	56	24	20	56	22	22
	10	55	20	25	55	18	27
	20	69	14	16	66	15	20
	35	72	15	13	67	16	17

The contribution was calculated as the proportion of OC and N stocks in aggregate to those in bulk soils. MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm).

were expected because OC and N from forest litter are usually first incorporated into topsoil and then transported to deep soil. Moreover, the topsoil contains large amounts of labile organic matter that is sensitive to afforestation practices, which then easily decomposes into OC and N.

The OC and N concentrations and BD together determined the OC and N stocks. Our results showed that soil BD decreased by 17 % after 35 yrs of afforestation (Fig. 2), likely due to the increased forest litter, above- and belowground biomass, and soil porosity (Nadal-Romero et al., 2016), as well as reduced compaction of soil particles from no-tillage and the absence of agricultural machines (Burst et al., 2020). After 35 yrs of afforestation, the OC and N concentrations increased by 91 % and 73 %, respectively, leading to a final increase in the OC and N stocks. Our results also suggested that there was a significant negative correlation between soil BD and OC or N stocks and between the absolute change in soil BD and the absolute change in the soil OC stock in bulk soil (Fig. 5).

4.2. OC and N sequestration in water-stable aggregates

The land-use change from agricultural land to forest accelerated soil particle aggregation, with an increased MA fraction but decreased MI and SC fractions (Fig. 3, Nadal-Romero et al., 2016; Zhang et al., 2018), mainly due to accumulated organic matter (including litter, above- and belowground biomass and exudates) which could facilitate the activity of microorganisms and promote the formation of soil aggregates (Liu et al., 2020; Six et al., 2000). As previously mentioned, accumulated organic matter can accelerate soil aggregation and increase the MA proportion (Zhang et al., 2018, in our study, MA% = 42.79 + 0.79 × OM, R^2 = 0.86, P < 0.0001). Additionally, the cessation of interference activities (including tillage and agricultural machines) in forest soil could decrease the breakdown of aggregates and increase the

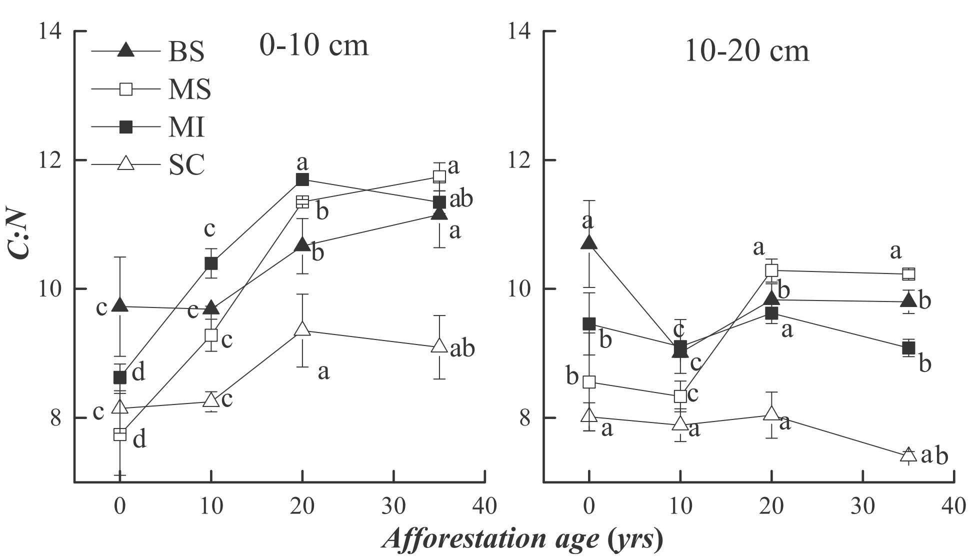

Fig. 4. The ratios of organic carbon to nitrogen (C:N) in bulk soils and aggregates after the conversion of agricultural land to forest. Afforestation age 0 represents the farmland. Means with the same lowercase letters within the same aggregate fraction are not significantly different at P < 0.05 among afforestation ages. Error bars are two standard errors of the means. BS: bulk soils; MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm).

Table 5
Relationship of soil nitrogen (*N*)-related parameters to organic carbon-(OC) related parameters in bulk soils and aggregates after the conversion of agricultural land to forest.

Parameters		Regression equation	R^2	P	RMSE
Concentration (g kg^{-1})	BS	N = 0.086 × OC + 0.172	0.97	< 0.0001	11.29
	MA	N = 0.077 × OC + 0.354	0.98	< 0.0001	14.31
	MI	N = 0.081 × OC + 0.264	0.99	< 0.0001	16.03
	SC	N = 0.089 × OC + 0.251	0.93	< 0.0001	6.27
Stock (kg m^{-2})	BS	N = 0.083 × OC + 0.028	0.96	< 0.0001	1.47
	MA	N = 0.783 × OC + 0.276	0.99	< 0.0001	1.78
	MI	N = 0.650 × OC + 0.102	0.92	< 0.0001	0.31
	SC	N = 1.271 × OC-0.010	0.94	< 0.0001	0.26
Overall input rate (g kg^{-1} yr^{-1})	BS	N = 0.081 × OC + 0.001	0.98	0.0002	0.20
	MA	N = 0.075 × OC-0.002	0.99	< 0.0001	0.44
	MI	N = 0.078 × OC + 0.002	0.99	< 0.0001	0.49
	SC	N = 0.080 × OC + 0.001	0.98	< 0.0001	0.08
Turnover rate constant (yr^{-1})	BS	N = 0.715 × OC + 0.010	0.77	< 0.0001	0.03
	MA	N = 0.684 × OC + 0.003	0.91	< 0.0001	0.05
	MI	N = 0.791 × OC + 0.004	0.96	< 0.0001	0.06
	SC	N = 0.849 × OC + 0.002	0.84	< 0.0001	0.03
Relative change (%)	BS	N = 0.746 × OC + 0.160	0.99	< 0.0001	1.09
	MA	N = 0.556 × OC + 0.084	0.99	< 0.0001	1.84
	MI	N = 0.648 × OC + 0.170	0.99	< 0.0001	2.25
	SC	N = 0.690 × OC + 0.081	0.99	< 0.0001	0.56
Absolute change (g kg^{-1})	BS	N = 0.078 × OC + 0.135	0.99	< 0.0001	7.27
	MA	N = 0.073 × OC-0.048	0.99	< 0.0001	11.77
	MI	N = 0.077 × OC + 0.011	0.99	< 0.0001	13.88
	SC	N = 0.085 × OC + 0.062	0.99	< 0.0001	2.78

BS: bulk soils; MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm); RMSE: root mean squared error of the model. Turnover rate constant and overall input rate for OC or N were fitted by a first-order model. Relative change means the percent change of OC or N concentration across the afforestation chronosequence. Absolute change means the absolute change of OC or N concentration across the afforestation chronosequence. The relative and absolute changes were all calculated using farmland as control.

MA fraction (Laganière et al., 2010).

The higher OC concentrations in the MA and MI fractions agree with the aggregate hierarchy theory that the OC concentration increases with increasing aggregate-size class (Six et al., 2000). We also observed higher N concentrations in the MA and MI fractions, which agrees with another study (Qiu et al., 2015). Furthermore, the increase in the proportion of MA after afforestation could physically better protect OC and N against decomposition by microbes (Liu et al., 2020; Razafimbelo et al., 2008), thereby leading to the accumulation of OC and N in this coarse fraction.

Based on the calculation formula, soil BD, aggregate mass proportions and aggregate-associated OC and N concentrations determined the aggregate-associated OC and N stocks. For example, even though the BD decreased with afforestation age, the greater increase in the MA proportion as well as the MA-OC and MA-N concentrations with afforestation age led to an increase in the MA-OC and MA-N stocks (Fig. 3). In contrast, even though OC and N concentrations in MI and SC increased with afforestation age, the decrease or slight changes in the MI and SC fractions (Fig. 3), together with the decreased BD (Fig. 2) likely contributed to fewer changes in the OC and N stocks in MI and SC (Fig. 3). Our results suggested that soil BD was significantly related to soil OC or N stocks (Fig. 5), and the change in soil BD was also

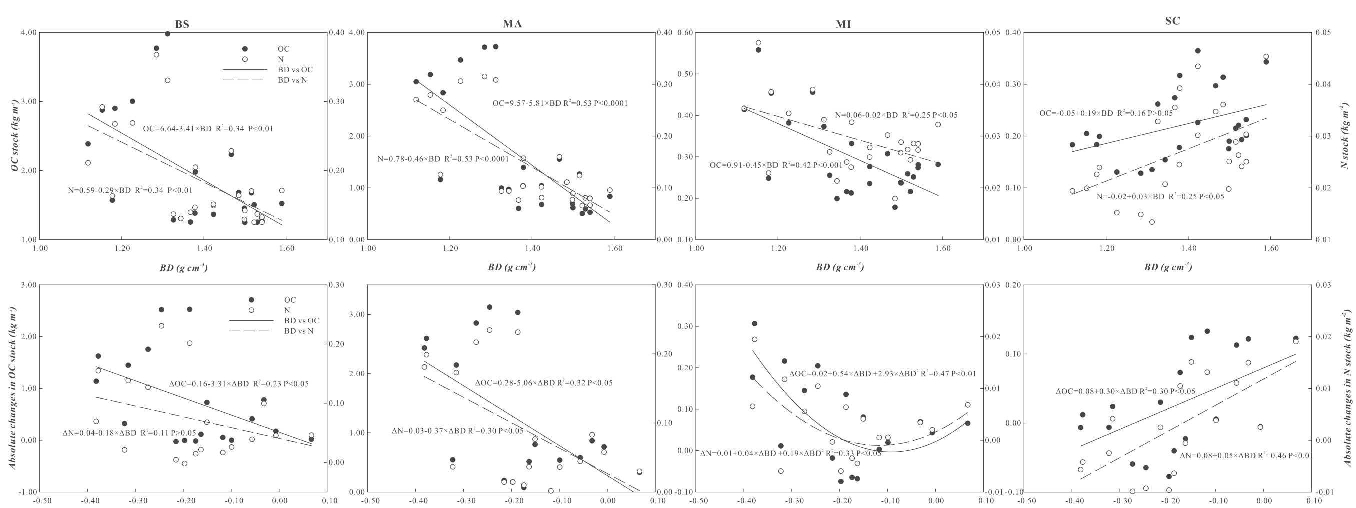

Fig. 5. Relationships of organic carbon (OC) and nitrogen (N) stocks to soil bulk density (BD) (Upper) and of changes in OC and N stocks after conversion of agricultural land to forest to changes in BD (Lower) in bulk soils and aggregates. Δ indicated the absolute changes in parameters. The absolute changes were calculated by subtracting farmland (reference) from afforested land with various stand ages. For each panel, the left y-axis represented OC stock or absolute changes of OC stock, the right y-axis represented N stock or absolute changes of N stock. BS: bulk soil; MA: macroaggregates; MI: microaggregates; SC: silt + clay (< 0.053 mm).

correlated with changes in the OC or N stock in aggregates (Fig. 5).

Furthermore, OC and N in MA showed marked increases during the first 20 yrs of afforestation and slower increases thereafter (Fig. 3). Similar results were also found by Deng et al. (2014a), who reported that OC storage, OC, total N, and C:N ratio increased rapidly with time and reached a peak at approximately 50 yrs of restoration and then stabilized during the later stage (> 50 yrs), in long-term (approximately 150 yrs) secondary forest succession in the Ziwuling Forest Region, China. Our study showed that both the proportion of MA and the OC and N concentrations associated with MA increased during the first 20 yrs of afforestation (Fig. 3), leading to rapid increases in MA-associated OC and N stocks. After 20 yrs, the accumulation rates of MA-OC and MA-N concentration were lower than the increase rate in the MA proportion (Fig. 3), driving the slow increases in MA-OC and MA-N stocks (Fig. 3).

The mechanism of OC and N sequestration after the conversion of agricultural land to forest could be due to the temporal dynamics of inputs and the decomposition of plant litter. In the initial stages of afforestation, the litter in the forests was in direct contact with the surface soil, and the input of organic matter into the soil was comparatively greater than the decomposition, thus leading to higher OC and N from plant litter (Wainkwa Chia et al., 2017). In the late stages of afforestation, the newly input litter was not in direct contact with soils due to the existence of previous semi-decomposable litter between the soil and the new litter. The rate of newly input OC and N would thus be decreased, and the input and output of OC and N in above- and belowground areas would begin to balance out (Deng et al., 2014b). It could also be possible that the OC and N reached saturation status due to long-term high organic matter inputs. In our study, both the concentrations and stocks of soil OC and N tended to increase linearly along the afforestation chronosequence (Figs. 2 and 3). The increase in the N stock would be able to reduce the limitation of soil N, which is beneficial to OC sequestration over a long period of time. However, the C:N ratio was observed to gradually increase at the 0 − 10 cm soil depth (Fig. 4), which might be due to the relative increase in the N stock (0.01 kg m^{-2} yr^{-1}) being lower than that in the OC stock (0.04 kg m^{-2} yr^{-1}). In the long term, this may lead to progressive N limitation, which reduces C sequestration (Li et al., 2012).

Additionally, a higher aggregate proportion and higher amounts of aggregate-associated OC and N were observed in topsoil than in subsoil, which has been widely observed worldwide (Qiu et al., 2015; Wei et al., 2013). This result was expected because most processes affecting aggregation and the accumulation of OC and N (e.g., microbial activity, litter and roots) are more active in topsoil. For example, Liang et al. (2014) reported that greater litterfall and root inputs were found in the topsoil than in the deeper soil layer after afforestation. In addition, the topsoil was easily oxidized due to exposure to the atmosphere and was more likely to be disturbed by land-use conversion (Don et al., 2011). Our results indicate that during vegetation restoration, it takes longer to restore the subsoil than to restore the topsoil.

4.3. The turnover of soil OC and N

The MRT in bulk soil at 0 − 10 cm predicted in this study fell in the range of global MRT of OC at the 0 − 20 cm depth in terrestrial ecosystems (21.0–23.2 yrs) in the 1960–2008 period estimated by climate factors and the N model (Chen et al., 2013). The MRTs were shorter, while the k and I values of OC and N were greater in the topsoil than in the subsurface soil (Table 3), revealing that OC and N in the topsoil were more unstable, as reported by others (Six and Jastrow, 2002; Qiu et al., 2015). These results agree with the findings of other studies on the Loess Plateau of China. For example, Qiu et al. (2015) reported higher k and I values for OC in bulk soil at a depth of 0 − 10 cm (0.020 yr^{-1} and 0.876 g kg^{-1} yr^{-1}, respectively) than at a depth of 10 − 20 cm (0.013 yr^{-1} and 0.217 g kg^{-1} yr^{-1}, respectively) but shorter MRT at 0 − 10 cm (50 yrs) than at 10 − 20 cm (75 yrs) after 200 yrs of afforestation on the Loess Plateau, China. During the conversion from forests to croplands (e.g., deforestation), Wei et al. (2013) also found a higher k value but a lower MRT for OC in bulk soil at 0 − 10 cm (0.040 yr^{-1} and 25 yrs, respectively) than at 10 − 20 cm (0.017 yr^{-1} and 57 yrs, respectively).

Moreover, based on a comparison of MA and MI, SC had the lowest k and I values and longest MRTs for OC and N (Table 3), indicating that OC and N were more labile and susceptible to decomposition in the coarse fraction after land-use change from farmland to forest (Six et al., 2000; Solomon et al., 2002). This finding agrees with previous reports that MI- and SC-associated OC are more resistant to land-use change compared to MA-associated OC (Six and Jastrow, 2002; Wei et al., 2013). Additionally, the lower C:N ratio in the SC fraction (Fig. 4) also supported the idea that SC-associated OC is more recalcitrant (Six et al., 2004).

4.4. The correlation between OC and N

OC and N were synchronously sequestered after the land-use change from agricultural land to forest, regardless of the aggregate fraction and stand age, as distinctly shown by the significant linear relationship between OC and N in terms of the absolute changes, the relative changes, the overall input rate, and the turnover rate constant (Table 5). Similarly, Li et al. (2012) reported a strong linear correlation between the rates of absolute changes in C and N stocks in both organic and mineral layers in five climate zones in the USA. Our results are consistent with the theory that N dynamics could regulate C sequestration over a long period of time in terrestrial ecosystems (Luo et al., 2004; Knops and Tilman, 2000). For example, Melillo et al. (2011) showed that inorganic N released in the soil solution in a deciduous forest markedly increase long-term plant and soil C stocks in New England. The increase in soil C storage also led to the sequestration of N in a Lethent clay loam in the San Joaquin Valley (California) (Groenigen and Kessel, 2002). Our results highlight the need to take the C–N coupling relationship after land-use change into account to help understand biogeochemical cycling and subsequent feedback with climate change and land management.

We addressed the dynamics of OC and N in bulk soils and aggregates following 10–35 yrs forest establishment on abandoned farmland, which will provide an important understanding of afforestation in sequestering C and N in soils at a relatively wide range of temporal scales and thus the mitigation of atmospheric CO_2 concentrations. However, a relatively large fraction of C and N accumulate in the organic layers after the conversion of agricultural land to forest (De Marco et al., 2013; Sybryn et al., 2019). For example, De Marco et al. (2013) reported that soil C was sequestered at a rate of 5 − 70 g m^{-2} yr^{-1} and N was sequestered at a rate of 3.3 g m^{-2} yr^{-1} in the organic layer following afforestation of treeless sites. Therefore, the organic layer should be included in future research to support accurate predictions of OC and N dynamics in ecosystems.

5. Conclusion

In this study, we investigated the concentrations and stocks of soil OC and N and their dynamic relationship in bulk soils and aggregates after the conversion of agricultural land to forest. As shown in other studies, we found that the conversion of abandoned farmland to forest accelerated soil aggregation and sequestered OC and N in bulk soils and aggregates, mainly the MA. The soil depth and afforestation age significantly affected the soil BD, aggregation distribution, and OC and N in bulk soils and aggregates. The OC and N continued to accumulate with afforestation age but reached a plateau at approximately 20 yrs of conversion. Moreover, our results demonstrated that soil OC and N were synchronously sequestered after land-use change from agricultural land to forest, which was supported by a significant linear relationship between the OC and N in terms of the absolute changes, the relative changes, the overall input rate, and the turnover rate constant regardless of the aggregate fraction and afforestation age. Our study will help to better estimate the OC and N storage after land-use change and to understand the C—N coupling relationship, which will further facilitate comprehension of the C and N cycles.

Declaration of Competing Interest

The authors have declared that no conflict of interest exists.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.106866.

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