



Soil C:N:P stoichiometry in plantations of N-fixing black locust and indigenous pine, and secondary oak forests in Northwest China

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Abstract

Purpose Soil nutrient concentrations and stoichiometry are important indicators of plant growth, terrestrial productivity, and ecosystem functioning. Nevertheless, little is known about the vertical distribution and the environmental factors influencing the spatial patterns of different forest types under the “Grain for Green” program and the “Natural Forest Resources Protection” project in Northwest of China.

Materials and methods We collected 114 soil profile samples within a 0–100-cm depth from black locust and Chinese pine plantations, and secondary oak forests. We determined the vertical distributions of soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), and their ratios along environmental gradients in Shaanxi Province, Northwest China.

Results and discussion The results showed that both SOC and TN concentrations decreased exponentially within the soil profiles of the three forest types, but there was minimal change in TP. Significant differences in SOC, TN, and TP were found in the surface soil layers among the forest types. Both SOC and TN were relatively low in the N-fixing black locust plantations and TP was comparatively low in the Chinese pine plantations. The C:N:P ratios decreased with increasing soil depth for the three forest types. These ratios were comparatively high in the Chinese pine plantations, relatively low in the black locust plantations, and moderate in the oak forests. The differences in the ratios among the three forest types were more significant in surface soil than in deep soil. Precipitation was positively correlated with the concentrations of SOC and TN and the ratios of C:N:P. Temperature was negatively correlated with concentrations of SOC and TN and the ratios of C:N:P across all soil depths. A log-transformed linear C-N relationship was found for all three forest types, suggesting a well-constrained coupling between the levels of the two elements.

Conclusions Our results demonstrated the effect of different tree species on soil C:N:P ratios and their controlling factors within soil profiles along environmental gradients. The secondary oak forest accumulated soil C and N more effectively than the plantations. The Chinese pine plantations were relatively more susceptible to P limitation. Therefore, the mechanism of different

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plant species on soil biogeochemical processes at the whole soil profile level must be considered when developing forest management strategies and implementing vegetation restoration projects.

Keywords Forest types · Northwest China · Soil nutrient status · Spatial variability · Vertical distribution

1 Introduction

As the largest carbon (C) pool in the terrestrial biosphere, soil plays an important role in global C cycling. Soil C stores exceed those found in vegetation biomass and atmospheric reservoirs combined. Therefore, any minor change in soil

organic C (SOC) will have a significant impact on atmospheric carbon dioxide (CO₂) concentrations (Eswaran et al. 1993). Meanwhile, nitrogen (N) and phosphorus (P) are the key nutrients and limiting elements of terrestrial ecosystems. The availabilities of N and P in soil strongly influence primary production and C accumulation, and a tight correlation has been observed between the C and N in terrestrial biogeochemical cycles (Cleveland and Liptzin 2007). Therefore, a great deal of research worldwide has focused on the storage, pattern, and environmental controls of the spatial-temporal soil C:N:P stoichiometry across different soil types, biomes, topography, and vegetation types. These data have increased the understanding of biogeochemical cycles and the potential feedbacks of terrestrial ecosystems to global climate change (Jobbagy and Jackson 2000; Yang et al. 2007, Yang et al. 2008; Tarnocai et al. 2009; Wiesmeier et al. 2012; Bing et al. 2016; Wang et al. 2017).

Soil C:N:P stoichiometry is regulated by plant nutrient uptake, litterfall, and root exudates. Meanwhile, the physiological strategies of vegetation types to optimize use of limiting nutrients may also affect soil C, N, and P (McGroddy et al. 2004). The effects of vegetation type on soil C:N:P stoichiometry have been documented in many studies. They revealed that conifers and broadleaf trees have different impacts on soil C:N:P characteristics (Jobbagy and Jackson 2000; Chen et al. 2004; Li et al. 2005; Marin-Spiotta and Sharma 2013; Ma et al. 2015; Chai et al. 2015; Dawud et al. 2017; Feng et al. 2017). Moreover, an increasing number of studies also reported significant differences between plantations and natural/secondary forests in terms of soil C:N:P ratios (Chen et al. 2004; Li et al. 2005; Marin-Spiotta and Sharma 2013; Cao and Chen 2017). Soil C and N concentrations was lower in plantations than in natural forests (Behera and Sahani 2003; Lemenih et al. 2004; Lemma et al. 2006; Cao and Chen 2017), but higher in afforested agricultural lands than in natural forests (Wall and Hytonen 2005). A meta-analysis based on 73 published studies showed that soil C and N concentrations in plantations were 36 and 26.5% lower than those in natural forests, respectively (Liao et al. 2012).

Although large-scale soil C:N:P stoichiometry patterns have been surveyed regionally, continentally, and globally, the results have been inconsistent. This discrepancy could be explained in terms of vegetation type, climate zone, biome, soil order, and soil weathering stage (Jobbagy and Jackson 2000; Yang et al. 2007; Tarnocai et al. 2009; Tian et al. 2010; Wiesmeier et al. 2012; Bing et al. 2016; Feng et al. 2017; Wang et al. 2017). Therefore, soil C:N:P stoichiometry should be investigated under different types of plant restoration, particularly in Northwest of China which has experienced large-scale vegetation construction due to severe soil and water losses since the 1970s. The “Grain for Green” program and the “Natural Forest Resources Protection” project were launched in 1998 to restore ecological environments

across Northwestern China. They have provided many ecological benefits including increases in vegetation cover (Cui et al. 2015b), biodiversity conservation (Chen and Cao 2014), and forest C sequestration (Cui et al. 2015a; Cao and Chen 2017). However, little information is available on soil C, N, and P concentrations and their stoichiometries in the secondary forests under the aegis of the “Natural Forest Resources Protection” project. In addition, relative differences in soil C:N:P between secondary forests and plantations remain to be determined.

Knowing the effects of plantations and secondary forests on soil C:N:P stoichiometry helps assess soil nutrient status, biogeochemical equilibrium, and ecosystem stability. It also improves predictions for the effects of current and future changes in land use and cover on both regional and global C cycles (Bonner et al. 2013; Cao and Chen 2017). In this study, widely distributed N-fixing black locust (*Robinia pseudoacacia*) and indigenous Chinese pine (*Pinus tabulaeformis*) plantations, and secondary oak (*Quercus liaotungensis*) forests were selected in Shaanxi Province, Northwest China. The vertical distributions of their soil C:N:P stoichiometries were analyzed along environmental gradients from south to north regional climate. The first objective was to compare the vertical distributions and the ratios of the SOC, TN, and TP in the 0–100 cm soil profiles under the three forests. The second objective was to quantify the correlations between the spatial variations in soil C:N:P stoichiometry and selected environmental factors. The results of this study may help improve forest management and vegetation recovery.

2 Methods and materials

2.1 Study area

The study was conducted along a south to north gradient in Shaanxi Province, China (105°29' to 111°15' E and 31°42' to 39°35' N). Both mean annual temperature (18–6 °C) and mean annual precipitation (1400–320 mm) gradually declined from south to north. The vegetation type ranges from north subtropical broadleaf forest zone to warm temperate humid and semi-humid forest zone and moderate temperate arid and semi-arid desert grassland. The latest forest inventory data available for Shaanxi Province reports that the secondary oak forest, protected under the “Natural Forest Resources Protection” project, accounts for the largest proportion of forest area (50%) and timber volume (50%) in the whole province. The indigenous Chinese pine plantation also accounts for a large proportion of forested area (52%) and timber volume (51%) among all plantations. The fast-growing, N-fixing black locust has been widely planted across Shaanxi Province during the implementation of the “Grain for Green” program, with more than 70,000 ha planted over the past

few decades (Qiu et al. 2010). This deciduous N-fixing species is native to North America and was introduced to China from Europe at the beginning of the twentieth century (Shan et al. 2002; Cierjacks et al. 2013; Tsunekawa et al. 2014).

2.2 Field sampling and laboratory analysis

We compared soil C, N, and P stoichiometries in the large proportion of middle-age forests in N-fixing black locust and indigenous Chinese pine plantations (20–30-year-old) and in secondary oak forests (30–40-year-old) based on the forest inventory database of Shaanxi Province. These are the main types of forests covered under the “Grain for Green” program and the “Natural Forest Resources Protection” project implemented across Shaanxi. Black locust and Chinese pine plantations were planted on abandoned cultivated lands, while secondary oak forests were regenerated naturally on abandoned farmlands originally populated by native oak forests before being cleared. Furthermore, 12, 11, and 15 sampling sites were selected for black locust, Chinese pine, and oak forest, respectively, based mainly on the relative distribution of each forest types from south to north through Shaanxi (Electronic Supplementary Material, Fig. S1). All sampling sites were located far from human habitation and were neither fertilized nor irrigated. Longitude, latitude, and elevation were recorded at each site using a global positioning system (GPS).

Field soil sampling was conducted from July to August 2011. A total of 114 soil profiles were collected from 38 sites (three soil profiles per site) along the south to north gradient. Soil samples were taken from each profile at depth intervals of 0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, and 50–100 cm. Soil bulk density samples were collected using a standard 100 cm³ container and oven-dried at 105 °C for 24 h until a constant weight was obtained. Soil samples for C, N, and P analyses were air-dried for over 1 week, sieved through a 2-mm mesh, handpicked to remove plant detritus, and then ground in a ball mill. Soil organic carbon (SOC) was determined using the wet oxidation method (Nelson et al. 1996). Total N (TN) was measured using the Kjeldahl method (Bremner and Mulvaney 1982), and total P (TP) was determined using the HClO₄-H₂SO₄ colorimetric method (Parkinson and Allen 1975).

2.3 Climate data

Datasets containing the mean annual temperature (MAT) and mean annual precipitation (MAP) for each sampling site used were obtained from the China Meteorological Data Sharing Service System (CMDSSS; <http://cdc.cma.gov.cn/>). We analyzed the datasets and established correlations between MAT and MAP using geographic variables (longitude, latitude, and altitude) recorded at 52 meteorological stations across the region. We then estimated the temperature and

precipitation of the sampling sites based on the established regressions (Fang et al. 2001; Piao et al. 2003; Li et al. 2015). The regressions were calculated in this study as follows:

$$\text{MAT} = 62.431 - 0.005^*H - 0.606^*Y - 0.234^*X \quad (1)$$

$$r^2 = 0.964, P = 0.000$$

$$\text{MAP} = 602.549 - 101.111^*Y + 31.938^*X + 0.091^*H \quad (2)$$

$$r^2 = 0.753, P = 0.001$$

where X , Y , and H represent longitude, latitude, and elevation, respectively.

2.4 Estimation of SOC, TN, and TP

The SOC density for each soil profile was estimated from the following equation (Batjes 1996; Wiesmeier et al. 2012; Yang et al. 2007, 2008):

$$\text{SOCD}_i = \text{SOC}_i^* \text{BD}_i^* \text{T}_i^* (1 - \text{C}_i) / 100 \quad (3)$$

where SOCD_i , SOC_i , BD_i , T_i , and C_i are SOC density (kg m⁻²), SOC (g kg⁻¹), bulk density (g cm⁻³), soil thickness (cm), and volume percentage of the fraction > 2 mm at layer i , respectively. The same procedure was used to estimate the densities of TN and TP.

2.5 Statistical analysis

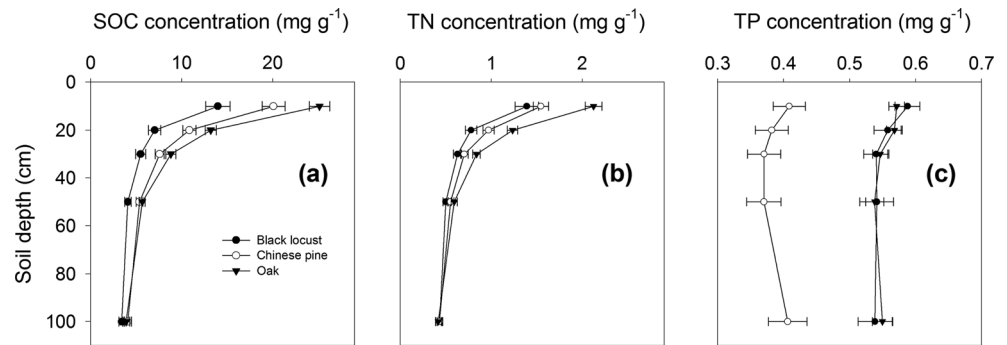
One-way ANOVAs were run with post hoc to determine whether the distributions of SOC, TN, TP, and the stoichiometric ratios of the three forest types differed significantly. A partial correlation analysis was used to examine the relationships among SOC, TN, and TP and the various environmental drivers, latitude, longitude, elevation, temperature, and precipitation (Wang et al. 2004). The level of statistical significance was set at $P < 0.05$. All analyses were performed using SPSS (version 20, IBM Corp., Armonk, NY, USA).

3 Results

3.1 Vertical distribution of SOC, TN, and TP

In all three forest types, SOC and TN concentrations decreased exponentially with soil depth in the top 0–1 m layer ($P < 0.001$; Fig. 1a, b). The SOC and TN concentrations were higher in the secondary oak forests than in both Chinese pine and black locust plantations within the first 30 cm ($P < 0.001$), but there were no significant differences in SOC and TN among the three forest types below 30 cm. In contrast, there

Fig. 1 Vertical distribution of the SOC (a), TN (b), and TP (c) concentrations for the three forest types



was minimal change in soil TP with increasing depth for the three forest types (Fig. 1c). The soil TP concentrations in the Chinese pine plantations were significantly lower than in the black locust plantations and the oak forests along the soil profile ($P < 0.001$, Fig. 1c). On the other hand, the soil TP concentrations in N-fixing black locust plantations were not higher than those of the secondary oak forests.

The SOC and TN densities for the three forest types also decreased within soil depth (the last two depth intervals converted to the equivalent of 10 cm thickness; Figs. 2 and 3). The SOC densities of the N-fixing black locust plantations were significantly lower than those of the Chinese pine plantations and secondary oak forests. They did not, however, significantly differ between the secondary oak forests and the Chinese pine plantations in the upper 30 cm layer

(Fig. 2). The soil TN densities were significantly higher in the secondary oak forests than these of black locust and Chinese pine plantations at 0–10 cm and 10–20 cm (Fig. 3). The soil TP densities of the N-fixing black locust plantations were significantly higher than those of the non-N-fixing forest types. The soil TP densities of the secondary oak forests, however, were significantly higher than that of the highest density in the Chinese pine plantation within the top 30. Nevertheless, little difference in soil TP density was found between the oak forests and the black locust plantations at depth intervals of 30–50 cm and 50–100 cm (Fig. 4). Approximately 50% of the SOC and TN stocks in the upper 1 m soil layer were stored within the top 30-cm depth interval, while the top 50-cm depth interval was stored about half of the total TP stocks in all three forest types (Figs. 2, 3, and 4).

Fig. 2 Vertical distribution of the densities (a–c) and the proportional distribution of SOC (d–f) in black locust plantations (a, d), Chinese pine plantations (b, e), and secondary oak forests (c, f). Different letters denote significant differences among forest types (LSD test, $P < 0.05$). Error bars represent standard deviation of the means

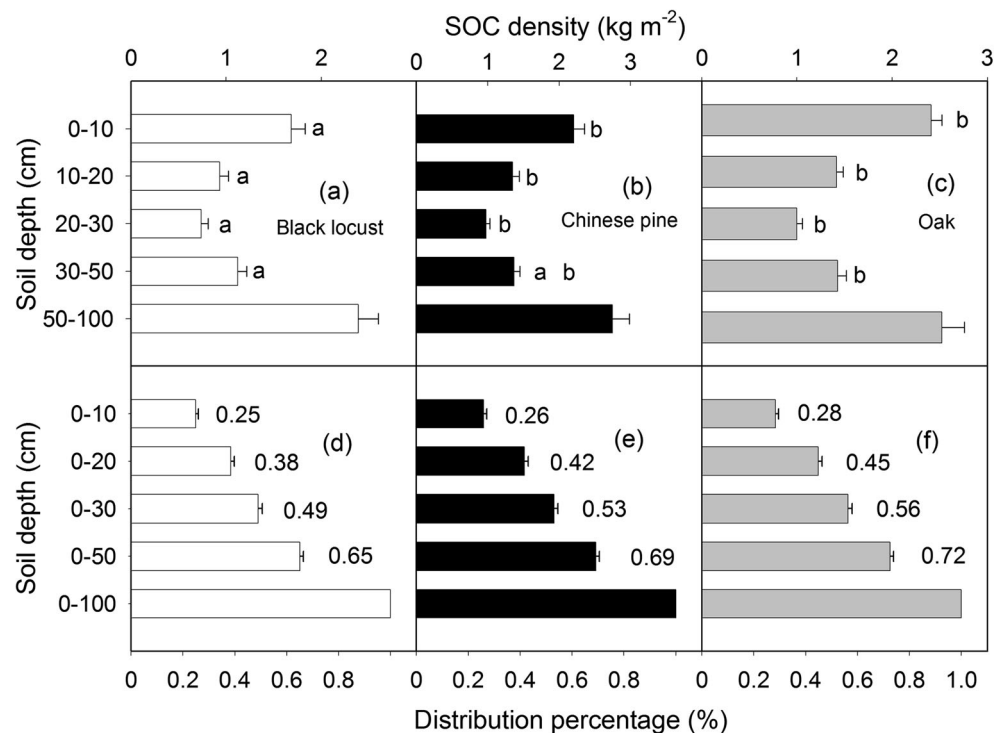
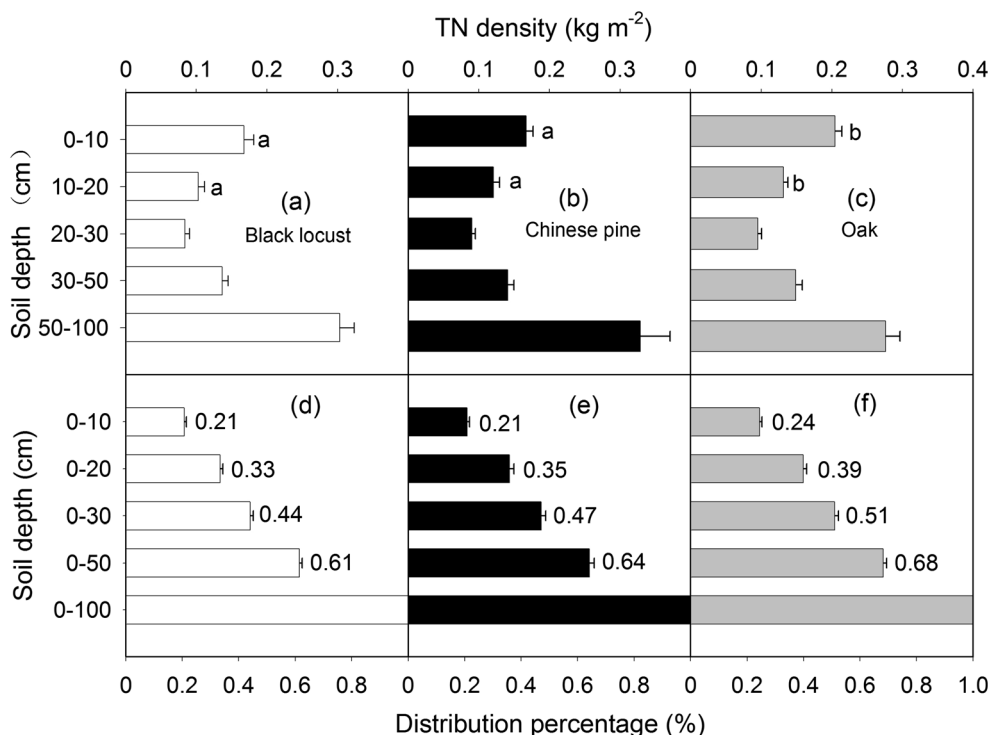


Fig. 3 Vertical distribution of the densities (a–c) and the proportional distributions of TN (d–f) in black locust plantations (a, d), Chinese pine plantations (b, e), and secondary oak forests (c, f). Different letters denote significant differences among forest types (LSD test, $P < 0.05$). Error bars represent standard deviation of the means



3.2 Vertical distributions of SOC, TN, and TP stoichiometric ratios

The soil C:N, C:P, and N:P ratios all significantly decreased ($P < 0.001$) with increasing soil depth (Fig. 5). The C:N ratio

varied only slightly along the profile with a coefficient variation of 11.17% compared to that of the C:P and N:P ratios. The ratios of C:N, C:P, and N:P were significantly higher in the Chinese pine plantations than those in the N-fixing black locust plantations at each depth interval (Fig. 5). Moreover, the

Fig. 4 Vertical distribution of the densities (a–c) and the proportional distribution of TP (d–f) in black locust plantations (a, d), Chinese pine plantations (b, e), and secondary oak forests (c, f). Different letters denote significant differences among forest types (LSD test, $P < 0.05$). Error bars represent standard deviation of the means

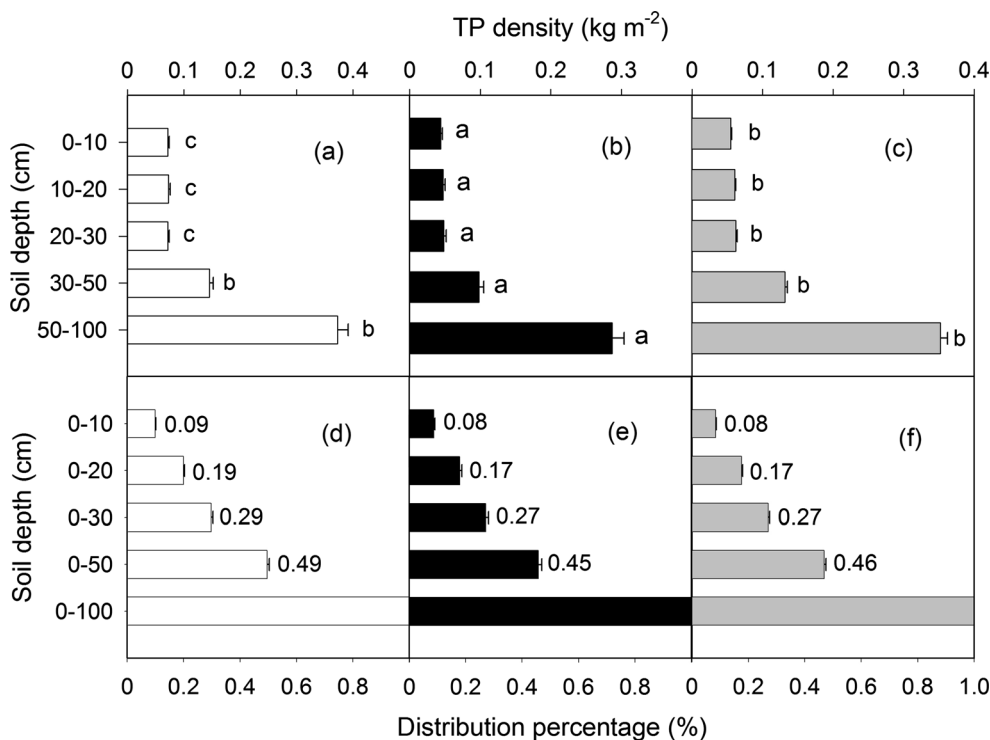
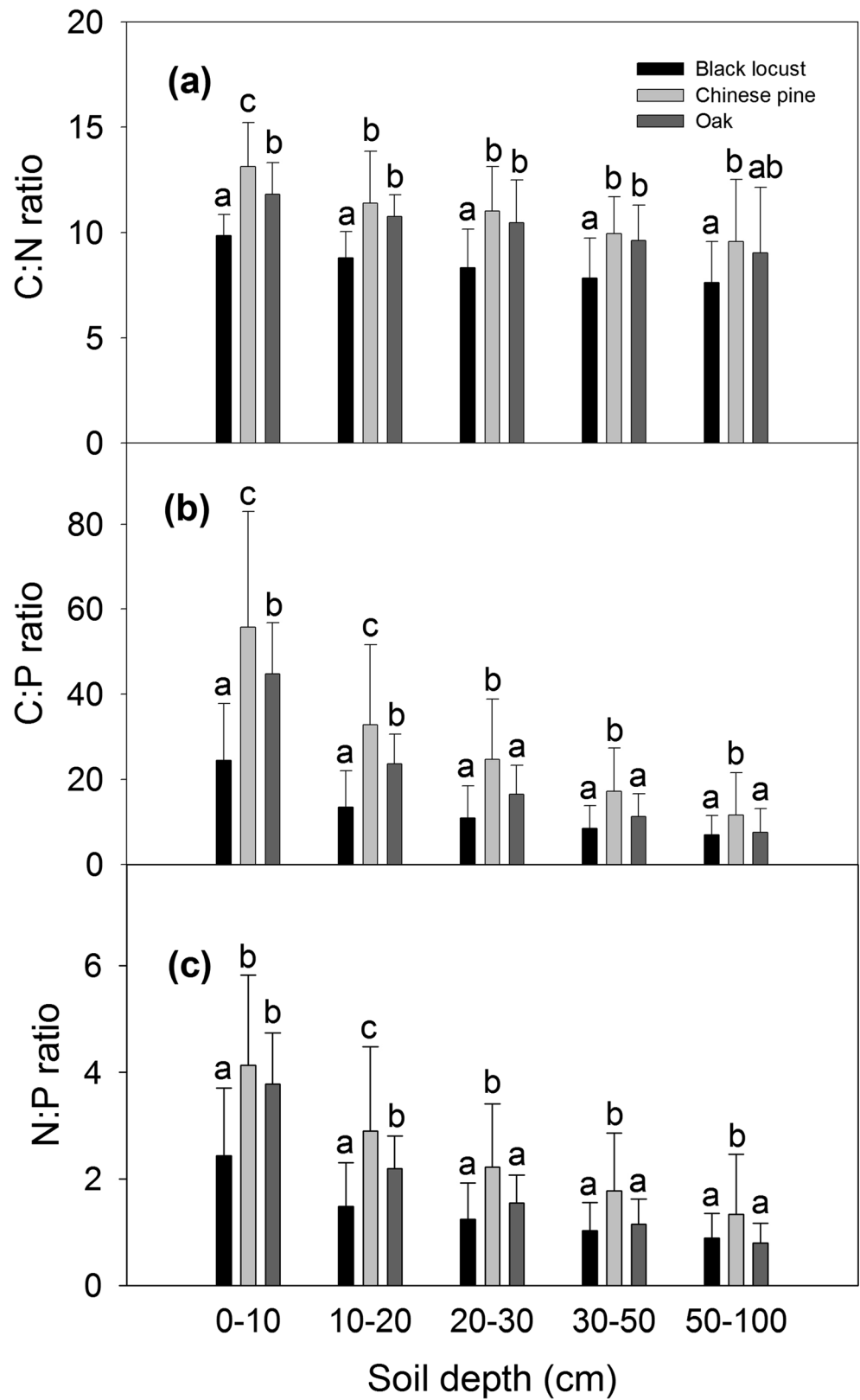


Fig. 5 Vertical distribution of C:N (a), C:P (b), and N:P (c) ratios for black locust plantations, Chinese pine plantations, and secondary oak forests. Different letters denote significant differences among these three forest types (LSD test, $P < 0.05$). Error bars represent standard deviation of the means



C:N:P values in the secondary oak forests were in between those for the black locust and Chinese pine plantations. The

differences among the three forest types were more significant in surface soil than in deep soil (Fig. 5).

3.3 Environmental controls of SOC, TN, and TP, and their spatial variations

The SOC, TN, and TP concentrations and their ratios exhibited significant spatial variations (Table 1). TP increased with latitude and decreased with longitude and elevation. All the correlations between TP and the geographic variables weakened with increasing soil depth. In contrast, the SOC and TN were significantly correlated with elevation at all soil depths but not with longitude or latitude (Table 1). The C:N, N:P, and C:P ratios were positively correlated with longitude and elevation but negatively correlated with latitude. The correlations were significant at almost each soil interval for N:P and C:P, but only weakly significant at the top 30 cm for C:N (Table 1).

Temperature and precipitation had strong impacts on soil TP, C:N, N:P, and C:P (Table 2). Temperature had a positive effect on soil TP whereas precipitation had a negative effect upon it. Conversely, N:P and C:P ratios were negatively correlated with temperature and positively correlated with precipitation (Table 2).

3.4 Relationships between SOC, TN, and TP concentrations

The TP concentrations were positively correlated with TN, but significantly correlated with SOC only at 0–30 cm (Table 3). There were, however, significant correlations between SOC and TN for all three forest types and all soil depths (Table 3, Fig. 6). In addition, an isometric relationship (the slopes of log-transformed C and N correlations were not statistically different from 1) between SOC and TN was observed in Chinese pine plantations at 20–100 cm and in oak forests in the top 20 cm, respectively (Table 4). In contrast, no isometric relationship was found for black locust plantations.

Nevertheless, the slopes of the stoichiometric C-N relationship did not significantly differ among the three forest types ($P > 0.05$).

4 Discussion

4.1 Vertical distributions of SOC, TN, and TP concentrations and ratios

In this study, the vertical distributions of the SOC, TN, and TP concentrations and their ratios were investigated in three different types of forest along a south to north gradient in Shaanxi Province, Northwest China. The results showed that, except for TP, the soil nutrient concentrations decreased along the soil profile. These results were consistent with findings from previous studies conducted in plantations on the Loess Plateau (Zhang et al. 2013; Song et al. 2016), subalpine forests of the eastern Tibetan Plateau (Feng et al. 2017), and other land use types (i.e., shrub, crop, and desert) worldwide (Jobbagy and Jackson 2000; Wang et al. 2004; Kahle et al. 2010; Chai et al. 2015). The decreasing trend with soil depth for SOC and TN was determined by the input pattern of organic matter in the soil, such as plant root and litter, which gradually decreased down the vertical profile. On the other hand, the soil TP profile pattern was mainly attributed to the parent material located in the bottom of the soil, which provided the major sources of P (Walker and Adams 1958). Long-term weathering of the parent material, together with an accumulation of P in the surface soil layer through translocation by plants, ultimately resulted in a relatively stable vertical TP distribution (Tian et al. 2010). Consequently, C:P and N:P declined much faster than C:N with increasing soil depth. This observation was consistent with the results reported in a

Table 1 Partial correlation coefficients of soil C, N, and P concentrations and ratios with longitude, latitude, and elevation in Northwest China

Soil depth (cm)	Longitude C	Latitude	Elevation	Longitude N	Latitude	Elevation	Longitude P	Latitude	Elevation
0–10	–0.094	–0.103	0.341**	–0.223*	0.035	0.242**	–0.597**	0.534**	–0.484**
10–20	–0.008	–0.166	0.339**	–0.149	–0.106	0.312**	–0.54**	0.437**	–0.366**
20–30	–0.004	–0.254**	0.359**	–0.133	–0.162	0.227**	–0.486**	0.476**	–0.37**
30–50	–0.041	–0.308**	0.392**	–0.094	–0.287**	0.301**	–0.458**	0.429**	–0.349**
50–100	–0.06	–0.234**	0.222*	–0.1	–0.254**	0.176*	–0.18	0.210*	–0.196*
	C:N			N:P			C:P		
0–10	0.411*	–0.505**	0.485**	0.363*	–0.507**	0.504**	0.421*	–0.552**	0.517**
10–20	0.398*	–0.367*	0.336*	0.371*	–0.551**	0.492**	0.460**	–0.555**	0.475**
20–30	0.347*	–0.451**	0.560**	0.394*	–0.593**	0.402*	0.448**	–0.614**	0.494**
30–50	0.190	–0.264	0.309	0.421*	–0.621**	0.428*	0.437**	–0.625**	0.509**
50–100	0.075	–0.060	0.010	0.068	–0.450**	0.323*	0.132	–0.463**	0.325*

** $P < 0.01$

* $P < 0.05$

Table 2 Partial correlations among soil C, N, and P concentrations and ratios with temperature and precipitation in Northwest China

Soil depth (cm)	Temperature			Precipitation		
	C	N	P	C	N	P
0–10	–0.319	–0.175	0.508*	0.166	0.03	–0.523*
10–20	–0.280	–0.317	0.465*	0.191	0.266	–0.424*
20–30	–0.271	–0.109	0.385*	0.393	0.243	–0.454*
30–50	–0.186	–0.128	0.358*	0.294	0.285	–0.375*
50–100	–0.125	–0.063	0.319*	0.303	0.232	–0.169*
	C:N	N:P	C:P	C:N	N:P	C:P
0–10	–0.394*	–0.419*	–0.419*	0.546**	0.564**	0.593**
10–20	–0.261	–0.390*	–0.363*	0.375*	0.592**	0.570**
20–30	–0.502*	–0.263	–0.366*	0.547**	0.594**	0.630**
30–50	–0.263	–0.282	–0.381*	0.321	0.622**	0.646**
50–100	0.002	–0.217	–0.219	0.044	0.488**	0.495**

***P* < 0.01

**P* < 0.05

nationwide synthesis of data compiled from many studies conducted in China (Tian et al. 2010). The soil surface layer (0–30 cm) interacts directly with the atmosphere and is the most sensitive to land-use changes (Batjes 1996; Wang et al. 2004). Differences in SOC and TN concentrations and their densities among the three forest types occur mainly within the 0–30 cm surface soil layers.

N-fixing species have been widely proven to increase the soil SOC and TN concentrations, N stores, N cycling and availability, and primary productivity in the recovery of degraded mining lands, deforested lands, and agroforestry systems (Deans et al. 1999; Uselman et al. 2000; Rice et al. 2004; Macedo et al. 2008; Wang et al. 2010). For example, soil organic matter and N concentrations in the 0–5 cm soil layer were 40–50% and 20–50% higher in the N-fixing forests than in the non-N-fixing forests, respectively, in the restoration of degraded lands of southern China (Wang et al. 2010). However, the current study and previous studies indicated that SOC and TN concentrations and densities in the soils under N-fixing black locust stands were lower than those under other species (Tateno et al. 2007; Song et al. 2016). Tateno et al.

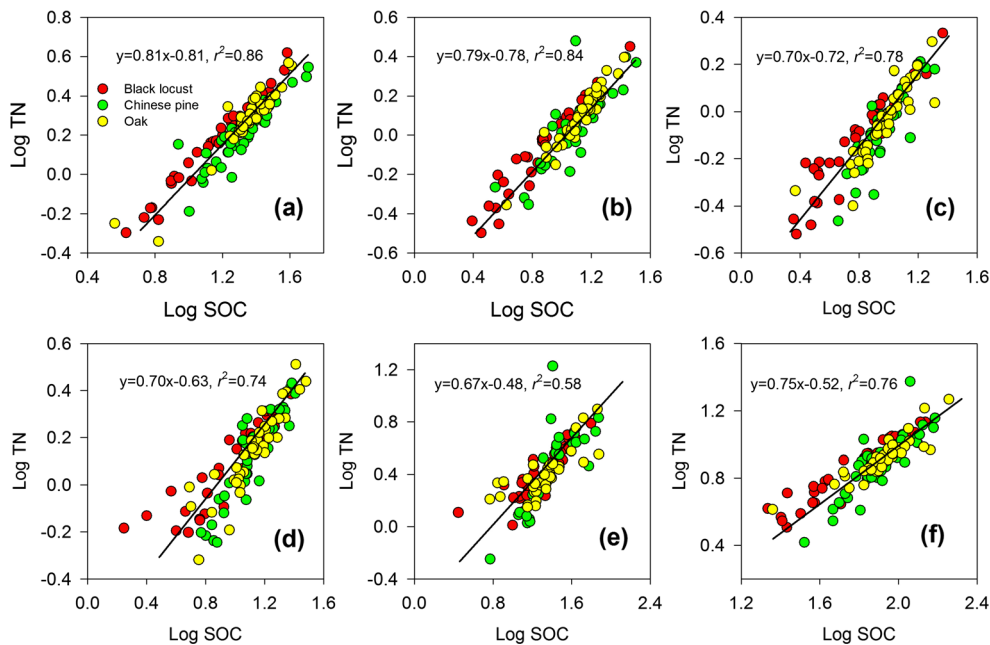
(2007) described high litter decomposition rates and low litter and soil organic layers inputs in the black locust plantations of the Loess Plateau. In addition, the fast litter decomposition rates of the black locust plantation can also be accounted for by the significantly lower soil C:N ratios in the black locust plantations compared to those under other forest types, especially in the surface soil layer (Bui and Henderson 2013; Zhao et al. 2015). A meta-analysis of 74 publications on the influence of land-use changes on soil C stocks revealed that soil C stocks in N-fixing tree species were not significantly higher than those under other tree species (Guo and Gifford 2002). The secondary oak forests in our field investigations had larger and thicker litter layers than those in the other forest types. Consequently, the soil under secondary oak forest had higher SOC and TN concentrations and densities than those under the black locust and Chinese pine plantations. Therefore, secondary oak forests were more effective at accumulating C and N than black locust and Chinese pine plantations.

Soil TP patterns are affected by the interactions among climate, vegetation type, and parent material (Sundqvist et al. 2014; Zhou et al. 2016). It is generally accepted that soil P concentrations in most regions of China, especially the Loess Plateau, are below the global average, resulting from low P inputs by weathering and strong losses by soil erosion and water runoff (Han et al. 2005; Zheng and Shangguan 2007; Zhou et al. 2016). In our study, we observed that soil TP concentration and density were significantly lower in the coniferous Chinese pine plantations than in the two broad-leaved forest types, which is mainly a result of more acidity in the foliage and litter of coniferous trees. Moreover, the concentrations of other P forms (i.e., the diluted HCl-extractable inorganic P) were significantly lower in coniferous forests than those in broadleaf forests of Chile and Southwest China (Thomas et al. 1999; Zhou et al. 2016). In addition, the

Table 3 Correlation coefficients among C, N, and P for different soil depth intervals

Soil depth (cm)	C-N		N-P		C-P	
	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>	<i>r</i>	<i>p</i>
0–10	0.934	0.000	0.564	0.000	–0.528	0.000
10–20	0.879	0.000	0.237	0.012	–0.251	0.008
20–30	0.912	0.000	0.318	0.001	–0.323	0.001
30–50	0.915	0.000	0.114	0.233	–0.16	0.094
50–100	0.595	0.000	0.108	0.258	–0.073	0.445
Total	0.845	0.000	0.219	0.021	–0.275	0.003

Fig. 6 Relationship between log-transformed C and N at different soil depths for black locust plantations, Chinese pine plantations, and oak forests. **a** 0–10 cm. **b** 10–20 cm. **c** 20–30 cm. **d** 30–50 cm. **e** 50–100 cm. **f** 0–100 cm. All fitting equations are significant ($P < 0.05$)



soil N:P ratios in the Chinese pine plantations were higher than those under the other two forest types which implied P limitation for growth of Chinese pine in the study area. Therefore, the synergistic effects of soil nutrient limitation with aggravating water deficiency conditions induced by global warming may threaten the recovery of Chinese pine plantations. These facts should be taken into consideration when planning forest management and ecological restoration.

4.2 Relationships between SOC, TN, TP, and environmental factors

Our analysis indicated significant effects of climate on soil nutrient concentrations and their ratios. Both SOC and TN concentrations were positively correlated with precipitation and negatively correlated with temperature, but not significantly. These results were consistent with those obtained from Chinese (Wu et al. 2003; Wang et al. 2004; Yang et al. 2007), American (Epstein et al. 2002), and global (Jobbagy and Jackson 2000) datasets. The SOC was determined from the

balance between plant biomass production input and the microbiological decomposition output (Post et al. 1982; Davidson and Janssens 2006). Increased precipitation may promote plant growth, thereby increasing soil C and N inputs in the form of litterfall and fine roots. Increases in temperature would accelerate the mineralization of soil organic matter and decrease both SOC and N (Fang et al. 2001; Wu et al. 2003; Yang et al. 2007; Chai et al. 2015). However, the combined effects of temperature and precipitation on SOC and TN are complex and not simply the sum of the individual influences of each factor (Jobbagy and Jackson 2000; Davidson and Janssens 2006). In our study area, both precipitation and temperature declined gradually from south to north, while precipitation was the main variable affecting SOC. Consequently, the SOC storage also decreased from south to north similarly to the precipitation gradients. The overall SOC storage in China is inversely proportional to temperature and directly proportional to precipitation. The correlation between SOC and temperature was stronger than that between SOC and precipitation (Wang et al. 2004). In contrast, both precipitation

Table 4 Analysis of log-transformed soil C and N relationships at different soil depth intervals for black locust plantations, Chinese pine plantations, and secondary oak forests

Soil depth (cm)	Black locust			Chinese pine			Secondary oak		
	Slope	Intercept	r^2	Slope	Intercept	r^2	Slope	Intercept	r^2
0–10	0.89	−0.87	0.98	0.79	−0.83	0.79	0.85	−0.87	0.88
10–20	0.85	−0.81	0.95	0.79	−0.81	0.69	0.91	−0.92	0.91
20–30	0.71	−0.68	0.89	0.93	−0.96	0.77	0.76	−0.78	0.78
30–50	0.59	−0.48	0.82	1.00	−0.99	0.82	0.83	−0.79	0.80
50–100	0.61	−0.36	0.77	0.97	−0.92	0.61	0.52	−0.29	0.59
Total	0.76	−0.48	0.91	1.04	−1.09	0.74	0.69	−0.41	0.77

Slopes not statistically different from 1.0 are indicated in italic type, and all equations are significant ($P < 0.05$)

and temperature significantly affect soil TP. Increased temperature accelerates the weathering of parent materials where the soil P originates, and an increase in precipitation facilitates the leaching of P from the soil. Therefore, soil TP increases with latitude and decreases with longitude because of the precipitation gradients in these two spatial variables. Soil TP also decreases with elevation since temperature falls with rising altitude. In our study, the N concentration increased and the P concentration decreased with increasing elevation (Table 3). The results of our study corroborate those previous reports which also stated that C and P concentrations, litter decomposition rates, and microbial N and P uptake and release all decline with increasing elevation (Sundqvist et al. 2014).

A linear log-transformed soil C-N relationship was found in all three forest types, suggesting a closely linked interaction between SOC and TN. Since the slope of the C-N stoichiometric relationships was not statistically different from 1.0, the SOC and TN were scaled isometrically in both the Chinese pine and oak forests. Similar soil C-N isometric patterns were also documented in a global forest meta-analysis (Cleveland and Liptzin 2007; Yang and Luo 2011). These trends may reflect the isometric C-N stoichiometry of plants from which soil C and N originate (McGroddy et al. 2004; Cleveland and Liptzin 2007). Certain studies, however, found no isometric C-N stoichiometry in plants, which complicated our understanding of the interaction between plants and soils (Yang and Luo 2011). This isometric stoichiometry was not examined between soil N (or C) and P at every depth in this study, although many studies have indicated a tightly linked relationship between N and P in plant leaves (Han et al. 2005; Reich and Oleksyn 2004; Reich et al. 2010) and fine roots (Yuan et al. 2011). A well-constrained soil N:P was noted in the Chinese (Tian et al. 2010) and global (Cleveland and Liptzin 2007) datasets. In both cases, only the surface (0–10 cm) had relatively consistent N:P ratios. Decoupling soil N (or C) and P in deeper soil layers is the result of differences in the main sources of these nutrients. The SOC was highly correlated with soil organic P and C, whereas N and P were moderately associated with the soil organic matter (Walker and Adams 1958).

5 Conclusions

Large-scale ecological restoration projects have been conducted in Northwestern China using different plant species, which have exerted profound effects on the dynamics and patterns of soil nutrients. Our field investigation examined the vertical distributions of soil C, N, and P concentrations and their ratios for the three major forest types in the region. We found that both SOC and TN decreased but TP only slightly decreased along the soil depth profile for all three forests. The concentrations and storage of SOC and TN in N-fixing black locust plantations were not higher than those in the indigenous Chinese pine plantations or the secondary oak forests.

Precipitation and temperature had significant effects on SOC, TN, and TP concentrations and their ratios. SOC and TN varied directly with precipitation and inversely with temperature. In contrast, TP is less significantly affected by climate since its source is primarily the parent material in the deeper soil strata. Since they grew mainly in arid and semi-arid nature of the region, Chinese pine plantations had lower soil TP densities and were more severely limited in terms of nutrient and water availability than the black locust and oak forests. Consequently, Chinese pine should be given particular attention when developing ecological restoration projects in the region.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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