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ORIGINAL ARTICLE

Ecological stoichiometry characteristics of the leaf–litter–soil continuum of *Quercus acutissima* Carr. and *Pinus densiflora* Sieb. in Northern China

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Abstract
To research the nutrient circulation laws of the pine-oak forest ecosystem, this paper studied the ecological stoichiometry characteristics of organic carbon (C), total nitrogen (N) and total phosphorus (P) in the two "leaf–litter–soil" continuums (*QAC: Quercus acutissima* Carr., *PDS: Pinus densiflora* Sieb.) in China and their intrinsic relationships. Results showed that (1) Contents of C, N and P in the two continuums were C > N > P, and total contents of the different components were leaf > litter > soil. (2) Ecological stoichiometry characteristics of C, N and P in the two continuums were C:P > C:N > N:P. For the different components, the C:N and C:P were litter > leaf > soil, and the N:P was leaf > litter > soil. (3) Content of C in leaves was higher than that of the global and Chinese values and indicated that their defense capabilities against outside environmental forces were very strong. While contents of N and P in soil were lower than that of the global and Chinese values. Therefore, attention should be paid to selecting nitrogen fixing species and strengthening the construction of a mixed forest in mountainous area of northern China and similar areas around the world.

Keywords Ecological stoichiometry · "Leaf–litter–soil" continuum · *QAC* and *PDS* · Mountainous area

Introduction

Ecological stoichiometry is the science of studying the balance of chemical elements in the ecosystem, emphasizing the relationship between the structure and function of organisms and ecosystems and the chemical element ratio between organisms and the environment (Reiners 1986; Elser et al. 1996). Ecological stoichiometry links different research fields, biological groups and biological studies of different scales by the ratio of different elements (Sterner and Elser 2002). Organic carbon (C), total nitrogen (N) and total phosphorus (P) are the most basic nutritional elements for the growth of vegetation (Sardans et al. 2012), and their ecological stoichiometric characteristics can reflect both the internal stability and the relationship of the plant organs. Moreover, they are important for determining the plant growth rates and nutrient use efficiencies and for assessing the limiting elements (Zhou et al. 2010; Niu et al. 2013).

At present, research on the application of ecological stoichiometry mainly includes the following aspects. (1) The studies on the ecological stoichiometric characteristics of global and regional scales indicated that the N:P of leaves decreased with increasing latitude, while the content of N and P did not change significantly (McGroddy et al. 2004; Kerkhoff et al. 2005). The response of the potency of N and P to temperature differs globally, and the potency of P increases with decreasing temperature, but the potency of N does not change significantly. By studying the ecological stoichiometry of C, N and P, Chinese scholars discovered that the N:P of Chinese plants was higher than that of the global ratio, probably due to the shortage of soil P in China. Different from the global trend, the contents of N and P in leaves in China increased as the temperature decreased, and the N:P did not change

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significantly (Han et al. 2005). Based on the forest ecosystem of the south-north sample belt in eastern China, the content of C and the C:N of leaves were significantly higher than the average global values, while the content of N and the N:P in leaves were significantly lower (Ren et al. 2007). (2) The studies on the ecological stoichiometric characteristics of different functional groups in ecological systems indicated that the C:N and C:P of temperate broad-leaved forests were less than those of temperate coniferous forests at a global scale, while the N:P was higher than that of temperate coniferous forests (McGroddy et al. 2004; Wang et al. 2011). Compared with the different functional groups, the contents of N and P in leaves of herbs were higher than those of woody plants, but the C:N and C:P of herbaceous leaves were lower than those of woody plants. In China, the N:P of evergreen forests, broad-leaved forests, deciduous forests and coniferous forests were 15.2, 15.1, 14.8 and 13.0 (Han et al. 2005), which indicated that the mean N:P in China was larger than the global mean, and the shortage of P is serious in Chinese forests. (3) The studies on the ecological stoichiometric characteristics of different components in the ecological system have mainly focused on changes in the C:N, C:P and N:P between plants, litter and soil. Jackson et al. studied the C:N:P of leaves, litter and fine roots across the globe and showed that the C:N:P of fine roots and leaves were close to 1158:24:1, but both were smaller than that of litter, probably due to the reabsorption process of nutrient elements(Jackson et al. 1997). Yan et al. studied the ecological stoichiometric characteristics of the leaves and litter of three natural forests in Zhejiang Province and found that the growth processes of broad-leaf forests mainly lack P, while deciduous broad-leaved forests mainly lack N and evergreen coniferous forests are limited by N and P (Yan et al. 2008). Nie et al. studied the C:N:P of the leaf–litter–soil continuum in the Poyang Lake wetlands and showed that differences in the leaf, litter and soil C:N:P ratios were significant, and the C:N, C:P and N:P of soil were significantly lower than that of leaves and litter (Nie et al. 2016). (4) The seasonal variation in ecological stoichiometric characteristics indicated that the content of substances and elements stored in the cell increased during the growth and development of plants during the phenological period, and the element ratio distribution also varied (Ren et al. 2007). Ågren found that the C:N and C:P of leaves gradually increased with the changes in the growing season, mainly because the expansion rate of leaf cells was faster than the nutrient element absorption of plant roots, which resulted in the dilution of the element concentration (Ågren 2008). Niu et al. studied the ecological stoichiometric characteristics of C, N and P in the leaves of 6 shrubs in the Alashan Desert, and showed that the ratios of C, N, and P in leaves largely changed throughout the growing season (Niu et al. 2013).

In the leaf–litter–soil microscopic continuum, changes in the soil nutrients available for plant growth, the nutrient demands of plants, and the amount of nutrients returned to the soil by litter make the nutrient dynamics in the leaf–litter–soil continuum demonstrate obvious differences (Delgado et al. 2016). At the same time, the nutrient cycling of the leaf–litter–soil continuum has a complex relationship with environmental factors and the leaf–litter–soil condition (Ladanai et al. 2010). The ecological stoichiometry of C, N and P is considered an important indicator of the C, N and P status of the ecosystem and is widely used to link the nutrient characteristics of the aboveground plants and underground soil (Laliberté et al. 2014). In addition, changes in these nutritive element cycles also influence the soil–plant ecosystem. Soil science is a land-related discipline, and it has important links to several of the UN Sustainable Development Goals (SDGs). If local eco-system services were maintained or restored, the soil health and soil functions will be enhanced, which directly feed into the realization of the SDGs (Keesstra et al. 2016, 2018). In recent years, the ecological stoichiometry characteristics of C, N and P in the leaf–litter–soil continuum and their intrinsic relationships have been widely considered by scholars at home and abroad.

In this study, two typical pine-oak species were used as the research objects, *QAC* (*Quercus acutissima* Carr.) and *PDS* (*Pinus densiflora* Sieb.) in northern China. Using field fixed-point sampling and indoor quantitative analyses, we studied the ecological stoichiometry characteristics of C, N and P of the "leaf–litter–soil" continuum and their intrinsic relationships. The purposes of this study were (1) to study the change characteristics of the C, N and P contents in the leaf–litter–soil continuum in *QAC* and *PDS*; (2) to explore the ecological stoichiometry characteristics of the C, N, and P in the leaf–litter–soil continuum and their intrinsic relationships in *QAC* and *PDS*; (3) and to reveal the nutrient cycle laws of the pine-oak forest ecosystem and provide a scientific basis for the research of ecological stoichiometry theory and the evaluation of ecosystem service function in the pine oak forest of the northern China.

Materials and methods

Description of site

The study was conducted at the Taishan Forest Ecosystem Research Station (E117°04′–117°22′, N36°16′–36°28′). It belongs to a typical mountainous area in northern China (Fig. 1). The altitude is from 310 to 950 m and the average altitude is 530 m. The climate is a warm temperate

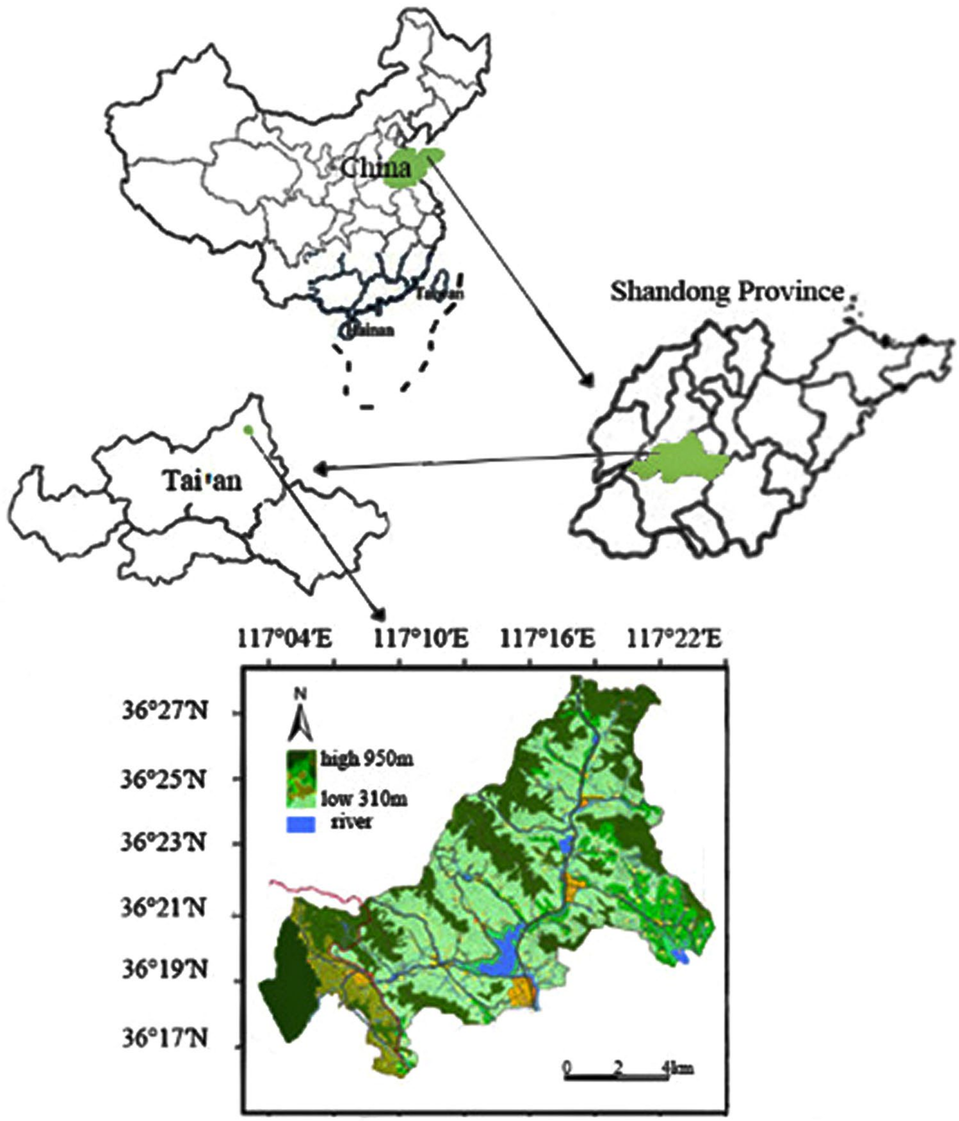

Fig. 1 Geographic location map of the study area

semi-humid monsoon climate, and the annual average air temperature is 18.5 °C. The mean annual precipitation is approximately 727.9 mm, and 75% of the rainfall is concentrated between June and September. The frostless season is 196 days. The soil type is brown soil. The vegetation types belong to coniferous forests and deciduous broad-leaved forests in the warm temperate zone, the main arbor species include *Quercus acutissima* Carr., *Pinus densiflora* Sieb., *Larix kaempferi, Castanea mollissima* and *Robinia pseudoacacia*, and so on.

Experimental design and sampling

Leaf, litter and soil sample collections were conducted in April, June, August and October 2016–2017. In the survey region, we selected *QAC* (30 years) and *PDS* (25 years) forest land as the sampling area (100 m × 100 m) (Table 1), which the altitude, coverage and age of the tree is close. The three sampling plots (20 m × 20 m) were set in each sampling area of the *QAC* and *PDS* forests. Because each sampling area had three replicates, there were 18 plots in total. We randomly and uniformly selected three trees in each sampling plot of the *QAC* and *PDS* forests and collected leaves from every tree canopy from the west, east, north, and south of the tree range. The leaves were mature, without diseases or insect pests on their blades. The petioles were removed, and then the leaves were mixed into composite samples for each tree before they were taken to the laboratory. The 54 leaf samples that were collected were dried to a constant-weight, ground in a 0.1 mm sieve and stored in sealed polyethylene bags for the C, N and P analyses. Next, we set 3 L traps (1 m × 1 m) in each sampling plot and then taken the litter to the laboratory. The treatment method for the litter was consistent with that of the leaves. Finally, we

Table 1 Basic status of typical forest stands of the study area

Plantation type	Sampling area number	Latitude	Longitude	Altitude (m)	Mean plant height (m)	Mean DBH (cm)	Crown density
QAC	1	N36°18′54″	E117°06′37″	478.92	13.32	11.27	0.81
	2	N36°19′24″	E117°06′54″	481.66	13.26	11.25	0.79
	3	N36°18′19″	E117°07′18″	480.23	13.25	11.26	0.79
PDS	1	N36°18′21″	E117°07′39″	714.36	11.81	13.02	0.75
	2	N36°18′43″	E117°08′13″	713.74	11.80	13.05	0.77
	3	N36°19′05″	E117°08′46″	713.98	11.80	13.00	0.76

QAC, *Quercus acutissima* Carr.; PDS, *Pinus densiflora* Sieb.

collected soil samples at the 0–30 cm deep layer according to the "S" type route. The soils, after air drying, were sifted in a 0.1 mm sieve.

The content of C in leaves, litter and soil was analyzed with the $K_2Cr_2O_7$ oxidation-external heating method. The content of N in leaves and litter was measured by the H_2SO_4–H_2O_2 digestion method, and that of the soil was measured with the Kjeldahl method. The content of P in leaves, litter and soil was analyzed by the Mo–Sb antispetrophotography method (Bao 2010).

The air temperature and precipitation were determined by the CR3000 automatic weather station of (Campbell Scientific, the United States). The weather station automatically recorded the observation data daily and every 10 min and the data were collected every 30 days.

Statistical analysis

For all the data, a one-way analysis of variance (ANOVA) was performed for the content and the ecological stoichiometry characteristics of the C, N and P in the leaf–litter–soil continuum. A Pearson correlation analysis was performed for the C, N, and P and C:N, C:P, and N:P in the leaf–litter–soil continuum, and differences were considered significant at $p < 0.05$. The statistical and correlation analyses were performed with the SPSS 19.0 software, and the maps were made by OriginPro 8.6.

Results

Contents of C, N and P in the leaf–litter–soil continuum

The contents of C, N and P in the leaf–litter–soil continuum of *QAC* and *PDS* were C > N > P ($p < 0.05$). The contents of C, N and P in the leaf–litter–soil continuum components, for both species of tree, were leaf > litter > soil ($p < 0.05$). The contents of C, N and P in the leaf–litter–soil continuum of different components were significantly different.

The contents of C in leaves of *QAC* and *PDS* were 515.91 g/kg and 529.91 g/kg, respectively (Table 2; Fig. 2), while the leaf N contents were 14.21 g/kg and 10.85 g/kg, respectively, and the leaf P contents were 1.71 g/kg and 1.71 g/kg, respectively. The contents of C in litter of *QAC* and *PDS* were 396.71 g/kg and 421.80 g/kg, respectively, while the litter N contents were 9.77 g/kg and 7.43 g/kg, respectively, and the litter P contents were 1.33 g/kg and 1.08 g/kg, respectively. The content of C in leaves and litter of *PDS* were both higher than those in leaves and litter of

Table 2 Contents of C, N, P and their ecological stoichiometry characteristics of the leaf–litter–soil continuum of *QAC* and *PDS*

Plantation type	Component	C (g kg^{-1})	N (g kg^{-1})	P (g kg^{-1})	C:N	C:P	N:P
QAC	Leaf	515.91 ± 13.7Aa	14.21 ± 0.65Aa	1.71 ± 0.055Aa	36.31 ± 0.9Aa	301.70 ± 11.2Aa	8.31 ± 0.29Aa
	Litter	396.71 ± 17.8Ba	9.77 ± 0.55Ba	1.33 ± 0.045Ba	40.59 ± 1.1Ba	297.72 ± 8.8Aa	7.33 ± 0.23Aa
	Soil	33.44 ± 1.1Ca	1.74 ± 0.15Ca	0.45 ± 0.01 8Ca	19.19 ± 0.4Ca	75.13 ± 3.5Ba	3.92 ± 0.09Ba
PDS	Leaf	529.81 ± 14.9Aa	10.85 ± 0.5Ab	1.45 ± 0.04Aa	48.86 ± 1.2Ab	365.45 ± 10.8Ab	7.48 ± 0.2Aa
	Litter	421.80 ± 11.7Ba	7.43 ± 0.6Bb	1.08 ± 0.039Ba	56.75 ± 1.6Bb	390.55 ± 9.5Bb	6.88 ± 0.19Aa
	Soil	20.80 ± 0.8Cb	2.03 ± 0.1Cb	0.34 ± 0.015Cb	10.25 ± 0.3Cb	61.63 ± 3.1Ca	6.01 ± 0.17Bb

Different small letters in the same component meant significant difference among different species, and different capital letters in the same species meant significant difference among different components at $p < 0.05$

The numbers in Table 2 are the means of the 2 years (2016–2017)

QAC, *Quercus acutissima* Carr.; PDS, *Pinus densiflora* Sieb.

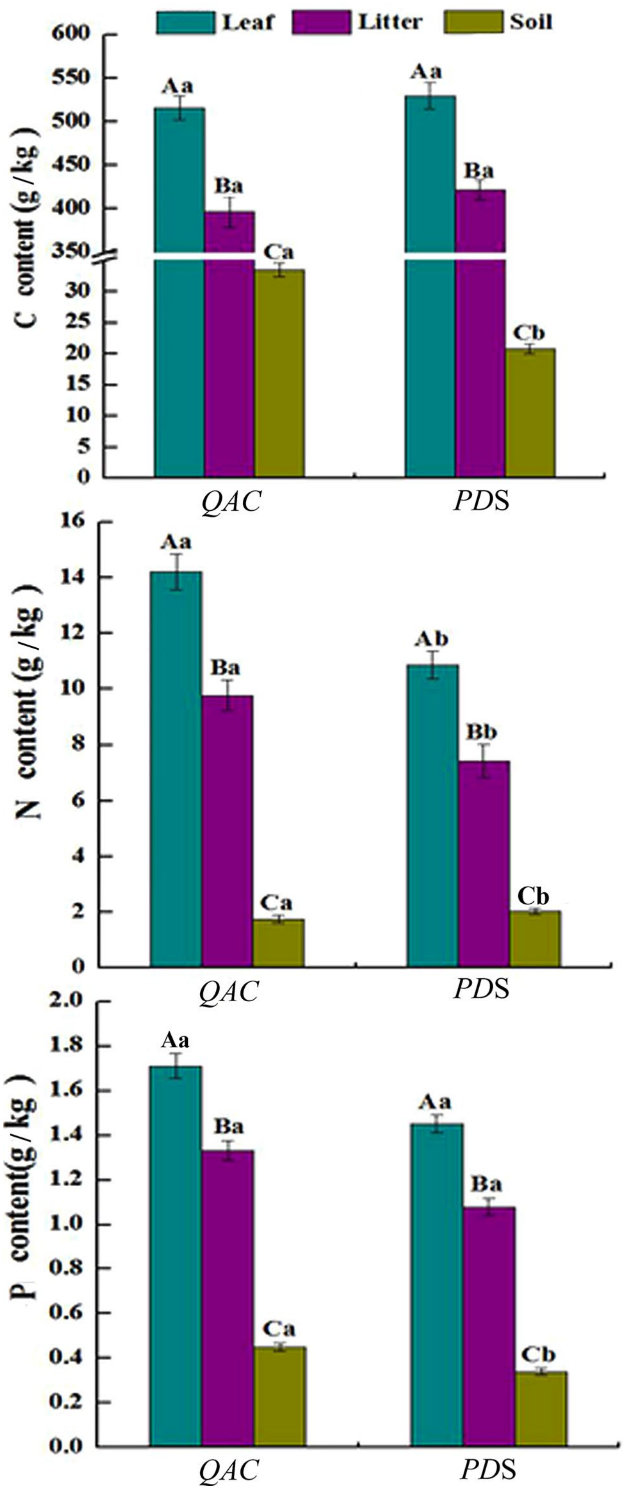

Fig. 2 Contents of C, N and P of the leaf–litter–soil continuum of *QAC* and *PDS*. *QAC*—*Quercus acutissima* Carr., *PDS*—*Pinus densiflora* Sieb., C—organic carbon, N—total nitrogen, P—total phosphorus, the same below. Different small letters in the same component meant significant difference among different species, and different capital letters in the same species meant significant difference among different components at $p < 0.05$

QAC, and the content of N in leaves and litter of *QAC* was higher than that of *PDS*.

The content of soil C (33.44 g/kg) of *QAC* was higher than that of *PDS* (20.80 g/kg), the content of soil N (1.74 g/kg) of *QAC* was lower than that of *PDS* (2.03 g/kg), and the content of soil P (0.45 g/kg) of *QAC* was higher than that of *PDS* (0.34 g/kg).

Ecological stoichiometry characteristics of the C, N and P in the leaf–litter–soil continuum

The ecological stoichiometry characteristics of C, N and P in the leaf–litter–soil of *QAC* and *PDS* were C: P > C: N > N:P ($P < 0.05$). The C:N and C:P of the leaf–litter–soil in different components were litter > leaf > soil ($P < 0.05$), and the N:P were leaf > litter > soil. The C:N, C:P and N:P of leaf and litter in *QAC* were significantly different from those of soil, the C:N and C:P of leaf and litter in *PDS* were significantly different from those of soil (Fig. 3).

The C:N of leaves in *QAC* and *PDS* was 36.31 and 48.86, respectively (Table 2; Fig. 3), and the C:P was 301.70 and 301.70. The C:N and C:P of *PDS* were significantly higher than those of *QAC*, which were 1.4 times and 1.2 times that of *QAC* The N:P was 8.31 and 7.48, which showed that the N:P in *QAC* was higher than that in *PDS*.

The C:N of litter in *QAC* and *PDS* was 40.59 and 56.75, and that in the *PDS* was significantly higher than that in the *QAC*, which was 1.4 times that of *QAC*. The C:P was 297.72 and 390.55, and the N:P was 8.31 and 7.48, which showed that the C:P and N:P in the *QAC* were higher than that in *PDS* (Fig. 3).

The C:N of soil in *QAC* and *PDS* was 19.19 and 10.25, and the C:P was 75.13 and 61.63. The C:N and C:P in *QAC* were significantly higher than those in the *PDS*, which were 1.9 times and 1.2 times those of *QAC* The N:P was 3.92 and 6.01, and the N:P of soil in the *PDS* was higher than that in the *QAC*, which was 1.4 times that of *QAC* (Fig. 3).

Seasonal dynamics of the ecological stoichiometry characteristics of C, N and P in the leaf–litter–soil continuum

Figure 4 showed that the C:N, C:P and N:P of leaves in *QAC* and *PDS* had an obvious seasonal change. During the growing season, the leaf C:N demonstrated the summer peak, while the leaf C:P reached its maximum in the spring. The leaf N:P of *QAC* was bigger in the spring and summer, and the leaf N:P of *PDS* was bigger in the summer and autumn. The changes in the C:N, C:P and N:P of litter were consistent with those of the leaves, as they were closely related to the leaf characteristics. The seasonal variation trends in the C:N and C:P in leaves of *QAC* and *PDS* were opposite to the changes in leaf contents of N and P, which is consistent

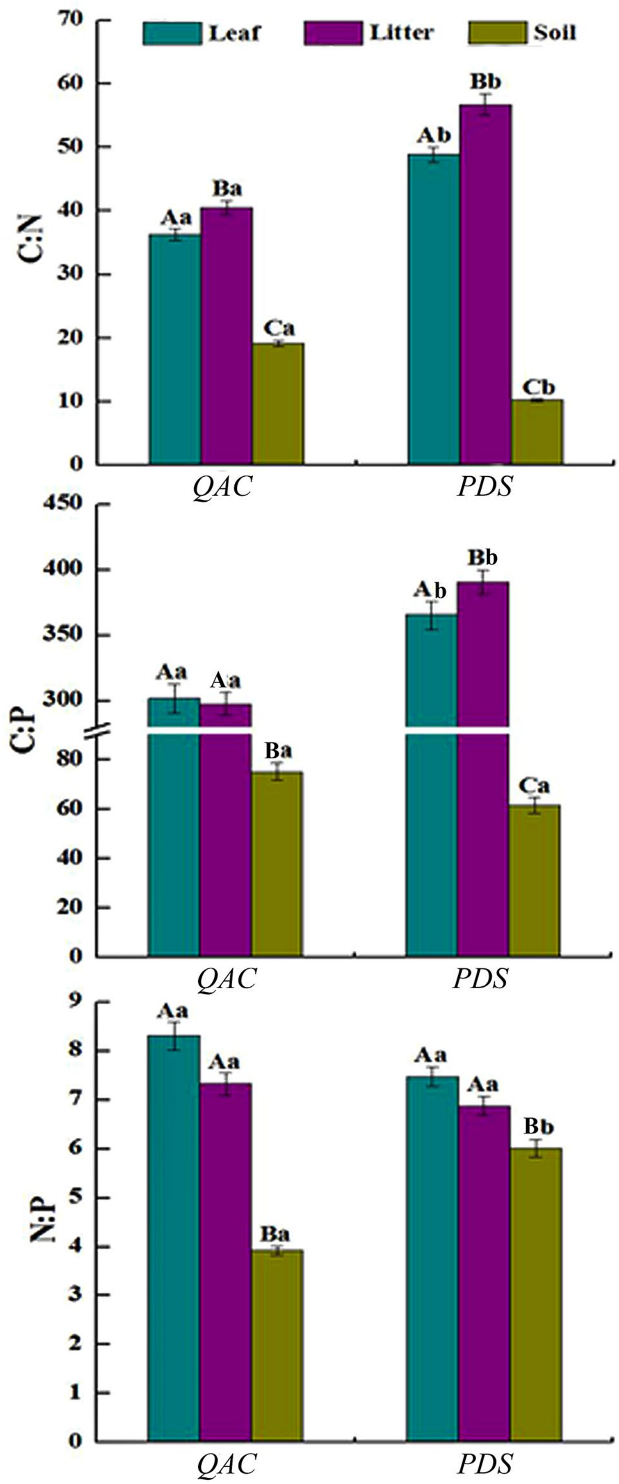

Fig. 3 Ecological stoichiometry characteristics of C, N and P of the leaf–litter–soil continuum of *QAC* and *PDS*. Different small letters in the same component meant significant difference among different species, and different capital letters in the same species meant significant difference among different components at $p < 0.05$

with the results of a study by Niu et al. (2013) when the leaf C:N was increased, the N use efficiency also increased, and the increases in the C:P indicated that the P use efficiency increased during this period (Wright et al. 2004). In our study, the contents of N and P were the lowest at the beginning of the growing season, and the carbon storage in the ecosystem was controlled by the availability of N and P. Low N and P contents indicated a relative excess of C, so the C:N and C:P were larger in this period, which is consistent with the result of Güsewell (Güsewell 2004).

Figures 5 and 6 showed that the ecological stoichiometry characteristics of C, N and P in leaves of *QAC* and *PDS* changed with precipitation and temperature during the growing season. First, with the increased in precipitation, the C:N ratio in leaves of *QAC* was decreased, although the change was not obvious, and the leaf C:P and N:P had a tendency to increase. There was a clear increasing trend for the C:N and N:P in leaves of *PDS*, but its leaf C:P decreased. Second, with the increased in temperature, the C:N, C:P and N:P in leaves of *QAC* were increased, but the change was not obvious. In addition, there was a clear increasing trend for the C:N and N:P in leaves of *PDS*, but the C:P ratio was decreased.

Discussion

Distribution characteristics of the C, N and P in the leaf–litter–soil continuum

The C, N, and P are essential elements for plant growth, which are as important as factors such as moisture, illumination, temperature and humidity (Song et al. 2012; Li et al. 2013). In our study, the contents of C in leaves of *QAC* and *PDS* were 515.91 g/kg and 529.91 g/kg, respectively, which were both higher than the mean global terrestrial leaf C content (464 g/kg) (Elser et al. 2000). If the content of C was higher in plant leaf, the photosynthetic and growth rates of leaf is lower, and its capability to defend against the outside environment is stronger (Wang and Shangguan 2011). Therefore, we reached that *QAC* and *PDS* had a very strong capability to defend themselves against the outside environment in the study area and that the defense capability of *PDS* was higher than that of *QAC* The N contents in leaves of *QAC* and *PDS* were 14.21 g/kg and 10.85 g/kg, respectively, which were both lower than the global mean for terrestrial plants (20.6 g/kg) (Elser et al. 2000) and Chinese terrestrial plants (20.2 g/kg) (Han et al. 2005). Likewise, it showed that the growth of *QAC* and *PDS* was restricted by N in the study area, which influenced the chlorophyll composition and the formation of the chloroplast, thus affecting the processes of plant growth and metabolism. The content of P in leaves of *QAC* was 1.71 g/kg, which was lower than the global mean

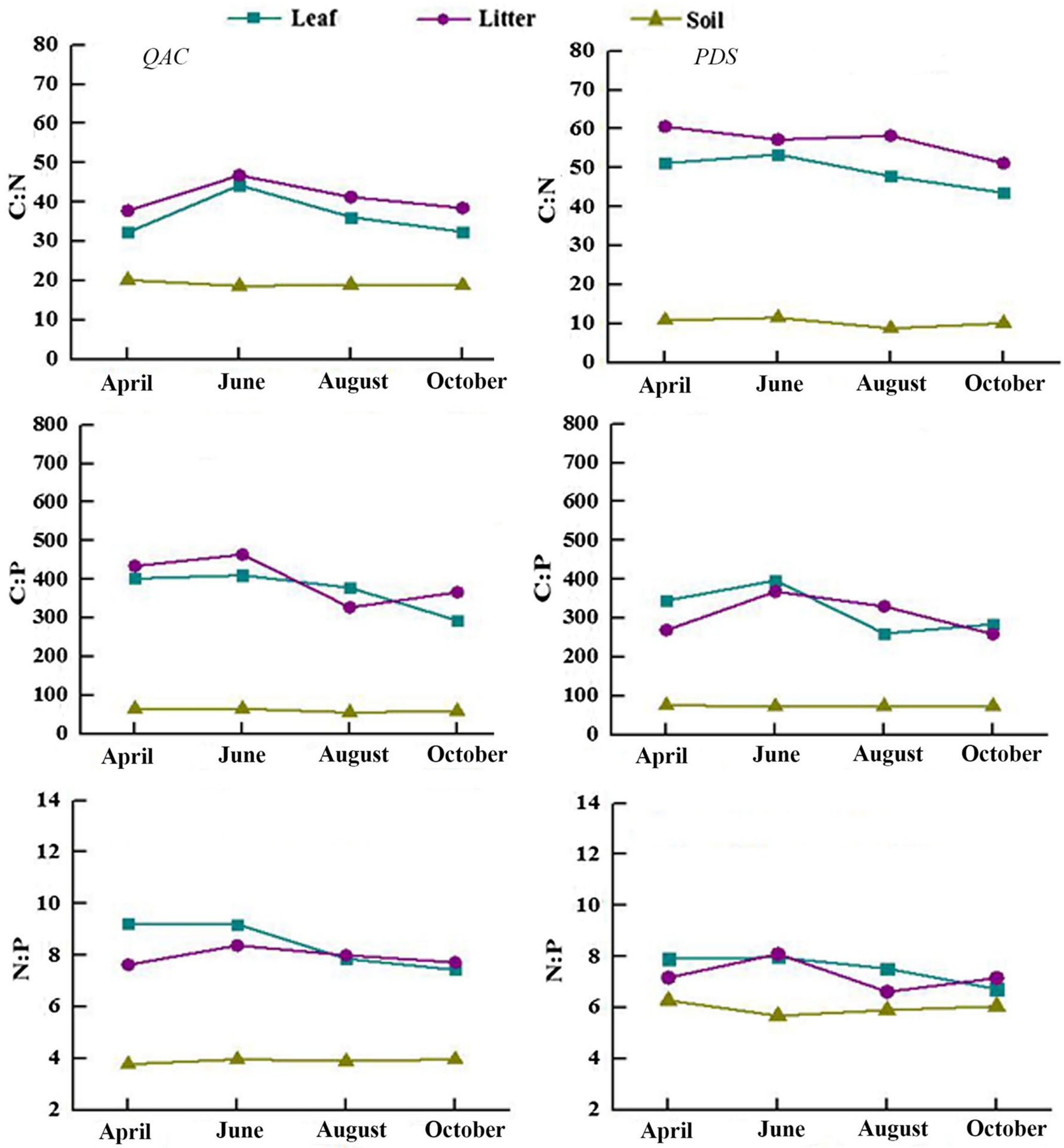

Fig. 4 Seasonal dynamics of the ecological stoichiometry characteristics of C, N and P of the leaf–litter–soil continuum of *QAC* and *PDS*

value for terrestrial plants (1.99 g/kg) (Elser et al. 2000) and higher than that in Chinese terrestrial plants (1.46 g/kg) (Han et al. 2005). The content of P in leaves of *PDS* was 1.45 g/kg, which was lower than the global mean value for terrestrial plants (1.99 g/kg) (Elser et al. 2000) and that in Chinese terrestrial plants (1.46 g/kg) (Han et al. 2005). This result showed that the growth of *PDS* was also restricted by P in the study area, and the growth was relatively slow.

The contents of C in litter of *QAC* and *PDS* were both higher than the global value (Yuan and Han 2009), showing that the levels of C in litter was relatively rich in the study area. The content of N in litter of *QAC* was the same as that at the global scale (10.9 g/kg), and the content of N in litter of *PDS* was lower than that at the global scale. The contents of P in litter of *QAC* and *PDS* were both higher than that at the global scale (0.85 g/kg) (Kang et al. 2010). Therefore, the contents of N and P in litter were consistent with those in the leaves, showing that litter and leaf characteristics were closely related. This is consistent with the results of Zeng et al. (2015).

The content of C in soil of *QAC* was 33.44 g/kg, which was higher than the global (25.71 g/kg) and Chinese (29.51 g/kg) values, and the content of C in soil of *PDS* was lower than the global and Chinese values (Tao et al. 2016).

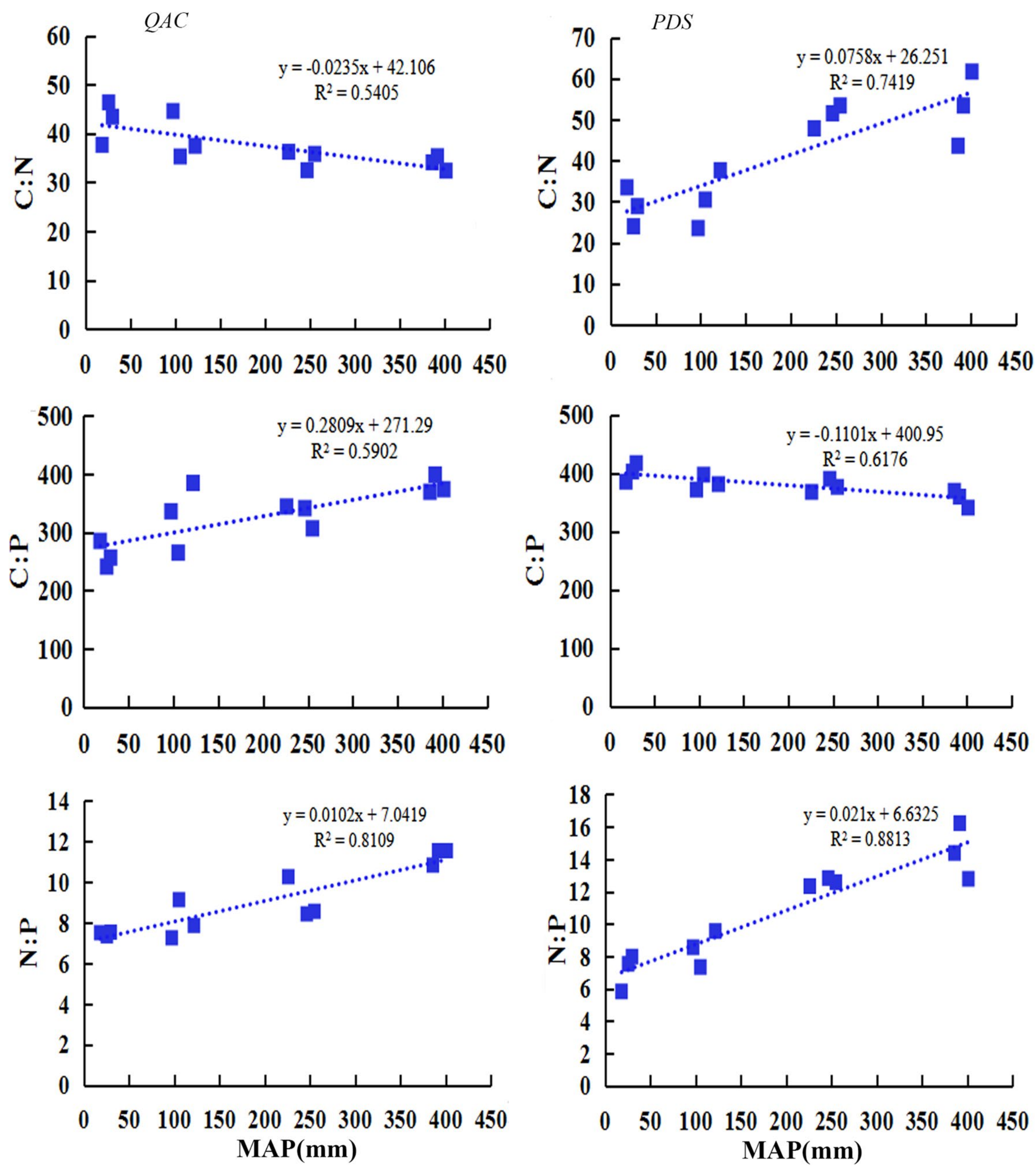

Fig. 5 Relationships between the stoichiometric ratio of C, N and P of leaf and MAP in *QAC* and *PDS*. *MAP* mean annual precipitation

The contents of N in soil of *QAC* and *PDS* were 1.74 g/kg and 2.03 g/kg, which were both lower than the global soil N content (2.1 g/kg) and the Chinese soil N content (2.3 g/kg) (Tian et al. 2010; Qing et al. 2015). The human activities on the land use are important, which can lead to great changes over a short period, and the vegetation types had significant effects on soil, root, litter, and living biomass C:N:P stoichiometry and soil nutrients (Gao et al. 2015). The different responses across species and plant types could balance the soil N and P stoichiometry (Yan et al. 2015). The oaks forest could protect the soil from the raindrop impact, generate deep, which favours infiltration and avoids surface runoff, while the pine cover results in higher soil losses (Cerdà et al. 2017). Mixed forests can increase the productivity and stability of forests, therefore, during the selection of plantation species, attention should be paid to selecting nitrogen fixing species (e.g., *Robinia pseudoacacia* L., *Amorpha fruticosa* L. and *Hippophae rhamnoides* Linn.) and strengthening the construction of theropencedrymion in the restoration of vegetation in the study area.

The contents of P in soil of *QAC* and *PDS* were both lower than the global (2.8 g/kg) and Chinese (0.56 g/kg)

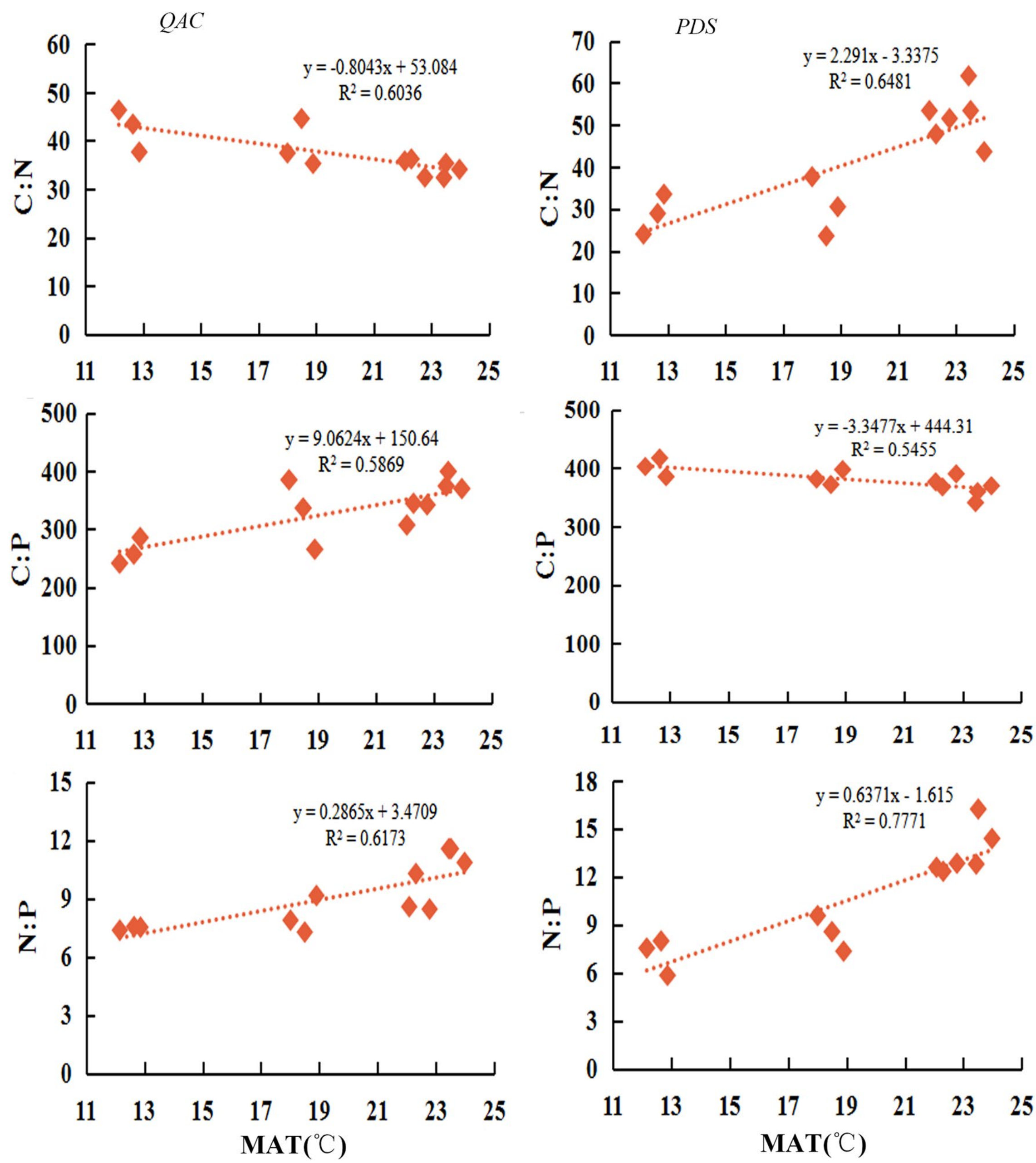

Fig. 6 Relationships between the stoichiometric ratio of C, N and P of leaf and MAT in *QAC* and *PDS*. *MAT* mean annual temperature

soil P contents (Tian et al. 2010; Qing et al. 2015), indicating that the study area seriously lacked soil P, which may be because the study area was a typical mountainous area of northern China, affected by severe soil and water loss caused the high leaching of soil P. This was also consistent with a study on soil P in China (Yang et al. 2014), which found that the Chinese level was significantly lower than the global level. The short of soil P was one of the key limiting factors of plant growth (Liu et al. 2016).

Analyses of the ecological stoichiometry characteristics of the C, N and P of the leaf–litter–soil continuum

The C:N and C:P of leaves reflect the use efficiency of N and P and the C fixation ability of the plants, and the C:N not only is controlled by the production of C and the absorption of nutrients but also plays a decisive role in the whole ecosystem of C and N use, storage and transfer (Xiang et al.

2006). In our study, the C:N of leaves in *QAC* and *PDS* were 36.31 and 48.86, respectively, which were lower than that in plants of the global forest ecosystem (37.1) and higher than that in plants of the Chinese forest ecosystem (28.5) (McGroddy et al. 2004, 33). In addition, the C:P was lower than that in plants of the global forest ecosystem (469.2) and the Chinese forest ecosystem (513.0). These results indicated that the use efficiency of P and the assimilation capacity of C were lower in this study area than the global and Chinese large-scale regions. The N:P of leaves is the most sensitive indicator of the nutritional status of the soil. Güsewell et al. (Güsewell 2004) found that when the leaf N:P < 10, the vegetation was relatively restricted by N; when the leaf N:P > 20, the vegetation was relatively restricted by P; and when the leaf N:P = 10–20, the vegetation was restricted by N or P according to plant-specific conditions, although the limited element varied with the environmental conditions. In our study, the N:P in leaves of *QAC* and *PDS*. were 8.31 and 7.48, respectively, and showed that they were generally restricted by N in the study area.

The ecological stoichiometry characteristics of the C, N and P in litter was influenced by both soil nutrient supply and plant nutrient utilization. When the soil supply of elements to the plants is lacking, and the plant reabsorb nutrients from the litter, the ecological stoichiometry characteristic of litter change (Franklin and Ågren 2002). In our study, the C:N and C:P in litter of *QAC* were lower than the global ratios for temperate broad-leaved forests (50.1, C:N; 659, C:P) (McGroddy et al. 2004), and the C:N and C:P in the of *PDS* were also lower than the global ratios for temperate coniferous forests (75.3, C:N; 910.8, C:P) (McGroddy et al. 2004). Moreover, The C:N in litter of *PDS* was higher than that in litter of *QAC*, which was consistent with results that showed the C:N in litter of temperate coniferous forests was higher than that in broad-leaved forests at a global scale. Studies have shown that when the C:N of litter was lower than 40, mineralized decomposition and the net release of N began to occur in the litter, and the lower the C:N and C:P, the faster the decomposition rate (Parton et al. 2007). In our study, the C:N in litter of both *QAC* and *PDS* were higher than 40, indicating that the decomposition mineralization of the litter was weak and that the release of N was relatively slow, whereas the rate of the release of N in the litter of *QAC* was higher than that in litter of *PDS* The N:P is an important index restricting the decomposition of litter, and low N:P ratios are beneficial to the decomposition of litter (Pan et al. 2011). The stoichiometric responses to P addition were scale independent, and altered plant C:N:P stoichiometry induced by P enrichment would stimulate organic matter decomposition and accelerate nutrient cycles (Mao et al. 2016). In our study, the N:P in litter of *QAC* and *PDS* were lower than the global ratio, which was beneficial to the decomposition of the litter in the study area.

Soil C:P is important for plant growth and development and indicates the potential for the release of P and the absorption and fixation of P from the environment (Wang et al. 2014; Zeng et al. 2015). In our study, the C:P in soil of *QAC* and *PDS* were lower than that of the global forest (81.9) (Tian et al. 2010), and showed that the soil P was seriously lacking, which was consistent with the abovementioned soil P contents in *QAC* and *PDS*.

Correlation analysis of the ecological stoichiometry characteristics of the C, N and P in the leaf–litter–soil continuum

Soil is the substrate for plant growth and the main source of nutrients for plant growth and development. Plants absorb water and nutrients with their roots, and they fix C by photosynthesis in the leaf to synthesize organic matter. Then, the organic matter returns to the soil by litter decomposition or nutrient transfer. Therefore, the content and stoichiometry characteristics of the C, N and P in the leaf–litter–soil continuum had relevance and difference (Ladanai et al. 2010). In our study, the content of C in leaves of *QAC* was significantly positively correlated with that in litter, the content of N in litter was significantly negatively correlated with that in the soil, and the leaf and soil C:N were significantly negatively correlated (Tables 3, 4). The results showed that C has a very good synergy between the leaves and litter of *QAC*; however, due to the relatively slow decomposition rate of the litter, the amount of N returning to the soil is relatively small, resulting in the increase of the C:N in soil. The C:P and N:P in litter and soil were significantly negatively correlated (Table 4), and the results showed that the soil C, N and P of *QAC* were mainly from the litter and influenced by P. When the P in litter is transferred to soil, the soil C:P and N:P would decrease.

Garnier (1998) found that, if plant growth was restricted by an element, the element concentration of the leaves was positively correlated with the ability of the soil to supply nutrients. In our study, the N and P in leaves and soil of *PDS* were significantly positively correlated (Table 3), and the change of of N and P in soil was an important reason for the difference of N and P in plant leaf, which was consistent with previous research results (Reich and Oleksyn 2004), and showing that the growth of *PDS* was restricted by N and P. The contents of P in litter was significantly positively correlated with that in soil (Table 3), showing that the accumulation of soil P mainly came from the decomposition of litter. The C:P of litter and soil was significantly positively correlated, and the N:P in litter and soil were significantly negatively correlated (Table 4), indicating that the litter and soil N and P had very good synergy.

The rates of plant biochemical reactions are controlled by the efficiency of N and P enzymes under low temperature,

Table 3 Contents of C, N and P of the leaf–litter–soil continuum correlation in *QAC* and *PDS*

Plantation type	Component	Leaf N	Leaf P	Litter C	Litter N	Litter P	Soil C	Soil N	Soil P
QAC	Leaf C	−0.836	−0.500	0.989*	−0.889	−0.956*	−0.482	−0.857	−0.773
	Leaf N	1	0.893	−0.902	0.959*	0.859	0.648	0.969*	0.932
	Leaf P		1	−0.612	0.785	0.572	0.629	0.827	0.838
	Litter C			1	−0.845	−0.975	−0.576	−0.922	−0.854
	Litter N				1	0.956*	0.781	−0.997**	0.977*
	Litter P					1	0.713	0.932	0.894
	Soil C						1	0.794	0.878
	Soil N							1	0.986*
PDS	Leaf C	0.016	−0.126	0.965*	0.083	0.507	0.691	0.493	0.413
	Leaf N	1	0.912	−0.135	0.982*	0.691	0.717	0.952*	0.799
	Leaf P		1	−0.342	0.954*	0.359	0.500	0.400	0.961*
	Litter C			1	−0.104	0.499	0.593	0.474	0.375
	Litter N				1	0.622	0.724	0.655	0.734
	Litter P					1	0.914	0.999**	0.987*
	Soil C						1	0.921	0.914
	Soil N							1	0.993**

QAC, *Quercus acutissima* Carr.; PDS, *Pinus densiflora* Sieb.

*Significance was tested at $p < 0.05$

**Significance was tested at $p < 0.01$

Table 4 Ecological stoichiometry characteristics of C, N and P of the leaf–litter–soil continuum correlation in *QAC* and *PDS*

Plantation type	Component	Leaf C:P	Leaf N:P	Litter C:N	Litter C:P	Litter N:P	Soil C:N	Soil C:P	Soil N:P
QAC	Leaf C:N	0.941	0.491	0.975*	0.954*	0.926	−0.988*	0.854	−0.995**
	Leaf C:P	1	0.756	0.857	0.819	0.773	0.932	0.825	−0.920
	Leaf N:P		1	0.334	0.280	0.219	0.481	0.437	−0.455
	Litter C:N			1	0.997**	0.990**	0.942	0.752	−0.990**
	Litter C:P				1	0.997**	0.913	−0.977*	0.704
	Litter N:P					1	0.878	0.650	−0.956*
	Soil C:N						1	0.923	−0.969*
	Soil C:P							1	−0.801
PDS	Leaf C:N	0.955*	0.667	0.892	0.716	0.320	0.550	0.954*	−0.197
	Leaf C:P	1	0.895	0.903	0.566	0.159	0.369	0.492	−0.059
	Leaf N:P		1	0.759	0.255	−0.097	0.053	0.122	0.152
	Litter C:N			1	0.323	−0.143	0.113	0.313	0.266
	Litter C:P				1	0.890	0.975*	0.981*	−0.825
	Litter N:P					1	0.965*	0.875	−0.990**
	Soil C:N						1	0.970*	−0.920
	Soil C:P							1	−0.800

QAC, *Quercus acutissima* Carr.; PDS; *Pinus densiflora* Sieb.

*Significance was tested at $p < 0.05$

**Significance was tested at $p < 0.01$

and if the activity of soil enzymes increase as temperature rises, this could promote the absorption of P and improve the N:P of soil by reducing the N:P of plants (Sardans et al. 2008). The ecological stoichiometry characteristics of the C, N and P of *QAC* and *PDS* were influenced by the variations in temperature and precipitation during the growing season of the study area, and they showed obvious seasonal variations, with results similar to those of a study on forest ecosystems (Ladanai et al. 2010). This was due to the changes in temperature and precipitation that were significant during different seasons in the study area, with more rainfall in the summer and a drier and lower temperature in the winter that affected the absorption of nutrient elements. Moreover, the input of P during the precipitation process was lower, which could lead to a significant increase in the soil N:P.

Conclusions

The contents of C, N and P in the leaf–litter–soil continuum of *QAC* and *PDS* were C > N > P. Their total content in the different components was leaf > litter leaves > soil. The differences in the C, N and P contents were significant among the different components, but the contents of N and P were not significantly correlated with that of C.

The ecological stoichiometry characteristics of the C, N and P in the leaf–litter–soil continuum of *QAC* and *PDS* were C:P > C:N > N:P; for different components, the C:N and C:P were litter > leaf > soil, and the N:P was leaf > litter > soil. The ecological stoichiometry characteristics of C, N, and P had obvious seasonal changes related to precipitation and temperature changes in the study area.

The content of C in leaves of *QAC* and *PDS* were high, indicating that their defense capabilities against outside environmental forces were very strong in the study area. The contents of N and P in the soil of *QAC* and *PDS* were lower than the global and Chinese values, and the soil P and N were seriously lacking. Therefore, attention should be paid to selecting nitrogen fixing species and strengthening the construction of a mixed forest (with species such as *Robinia pseudoacacia* L., *Amorpha fruticosa* L. and *Hippophae rhamnoides* Linn.) in the mountainous area of northern China and similar areas around the world.

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