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Spatial variations in soil organic carbon, nitrogen and phosphorus concentrations related to stand characteristics in subtropical areas

Fang Jiang · Xiaohong Wu · Wenhua Xiang · Xi Fang · Yeling Zeng · Shuai Ouyang · Pifeng Lei · Xiangwen Deng · Changhui Peng

Abstract

Aims Our study aimed to determine whether, and to what extent, stand characteristics and topography affected spatial variations in soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) concentrations in subtropical forests.

Methods Soil samples were taken from a *Choerospondias axillaris* deciduous broadleaved forest and a *Lithocarpus glaber–Cyclobalanopsis glauca* evergreen broadleaved forest. Spatial variations in SOC, TN and TP concentrations and the factors affecting them were investigated using geostatistical analysis and stepwise linear regression, respectively.

Results The *L. glaber–C. glauca* forest exhibited higher coefficients of variation (CVs) of SOC (35 %) and TN (34 %) concentrations than the *C. axillaris* forest (27 % for SOC and 21 % for TN), but the CV of TP concentration in the *L. glaber–C. glauca* forest (17 %) was lower than that in the *C. axillaris* forest (24 %). Stand characteristics contributed the most to spatial variations in SOC and TP, while soil texture made the greatest contribution to variations in TN. Topography contributed the least to variations in SOC, TN and TP.

Conclusions Stand characteristics, together with topography and soil texture, contributed to spatial variations in SOC, TN and TP concentrations. The contributions of stand characteristics differed in SOC, TN and TP due to their different cycling characteristics.

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Abbreviations

SOC	Soil organic carbon
TN	Total nitrogen
TP	Total phosphorus
CVs	Coefficients of variation

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Introduction

Forest soils are characterized by considerable spatial variations in soil chemical, physical and biological properties (Gonzalez and Zak 1994; Hoffmanna et al. 2014; Okin et al. 2008; Wang et al. 2013). Such variations inevitably affect biogeochemical processes such as carbon (C), nitrogen (N) and phosphorus (P) cycles in forest ecosystems (Luizão et al. 2004; Yuan et al. 2013). Owing to spatial variations, large uncertainties in soil organic carbon (SOC) stock estimates still remain (Gruba et al. 2015; Yuan et al. 2013). Given the importance of the forest soil C reservoir in the global C cycle, there is a need to improve the accuracy of SOC estimates by considering spatial variations in SOC. Soil N and P are vital components in building soil fertility (Hobbie 1992; Liu et al. 2015). Spatial variations in soil N and P concentrations are important factors affecting the coexistence of plant species by partitioning niches of nutrient utilization (Okin et al. 2008; Xia et al. 2015). Conversely, the coexistence of plant species may also generate spatial variations in soil nutrients by affecting soil nutrient cycling (Blair 2005; Okin et al. 2008). Therefore, a comprehensive understanding of spatial variations in SOC, N and P concentrations is important for accurately estimating SOC storage, and can further our knowledge of interactions between soil and plant as well as plant coexistence mechanisms within forest ecosystems.

The effects of stand characteristics on spatial variations in SOC and soil nutrients (such as N and P) have been addressed in previous studies (Bae and Ryu 2015; Hoffmanna et al. 2014; Xia et al. 2015; Yuan et al. 2013). These influences have been attributed to the fact that forest stands can potentially alter C and nutrients returned to the soil through leaf litter inputs, litter decomposition processes, root uptake, canopy composition, the basal area of trees and root/crowns (Bae and Ryu 2015; Blair 2005; Hoffmanna et al. 2014; Xia et al. 2015; Yuan et al. 2013). Recently, Xia et al. (2015, 2016) reported the exact nutrient inputs of leaf litter production that influence the fine-scale spatial heterogeneity of soil macronutrients and provided evidence that proves the persistence of soil nutrient patches. Previous studies of spatial variations in SOC and soil nutrients involved pure stands or mixed stands in temperate and tropical areas (Cremer et al. 2016; Xia et al. 2015; Yuan et al. 2013). In subtropical areas, however, knowledge of whether and how stand characteristics

influence spatial variations in SOC and soil N and P concentrations is still lacking. In addition, within a stand scale (i.e. different forest stands), the influences of stand characteristics on spatial variation patterns of SOC, N and P concentrations were evaluated mostly at a fine sampling scale ranging from one meter to several meters distance (Garten et al. 2007; Xia et al. 2015; Yuan et al. 2013). Variations in SOC, N and P concentrations at a coarse scale of ten meters distance in subtropical forests with diverse tree species have not been fully understood, although the variations at a coarse scale are of particular importance for comprehensively evaluating the influence of stand characteristics.

The distribution of tree species in natural forests tends to follow certain gradients in soil environments. Therefore, the effect of stand characteristics on SOC and soil nutrient concentrations usually varies depending on the topography, soil texture and pH value that exist in pure forest, or within a mix of tree species in temperate and tropical forests (Gruba et al. 2015; Schleuß et al. 2014; Schöttelndreier and Falkengren-Grerup 1999). Topographical factors, including elevation and convexity, can introduce large spatial variations in SOC and soil nutrients (Wang et al. 2007; Sheikh et al. 2009), and this is especially obvious under mountainous conditions, where topographic gradients are variable (Fantappiè et al. 2011; Yuan et al. 2013). Soil type, texture, pH value and soil moisture inherited from parent material are also important contributors to spatial variations in SOC, N and P concentrations (Liu et al. 2015; Rodríguez et al. 2009; Winowiecki et al. 2015). Yuan et al. (2013), for instance, found that 51 % of observed SOC variability could be explained by variations in soil moisture and pH value in a temperate forest. Distinctly, Liu et al. (2015) considered soil texture to be one of the key factors affecting spatial distributions of SOC and soil nutrients under Karst topography. Subtropical secondary forests consist of diverse tree species and are mainly distributed within mountainous and hilly areas. Therefore, stand characteristics, topography, soil texture and pH value may affect spatial variations in SOC, N and P concentrations. However, the relative contributions of the various factors are not fully understood.

We proposed two hypotheses: (1) that stand characteristics were the important factors affecting spatial variations in SOC, total N (TN) and total P (TP) concentrations in subtropical forests; and (2) that the magnitude of the effect of stand characteristics on spatial variations varied among SOC, TN and TP because other factors

(such as topography, soil texture and pH value) also affected SOC, TN and TP concentrations and C, N and P had different cycling characteristics. If the hypotheses were correct, we would expect to observe differences in the spatial variations in SOC, TN and TP concentrations, and the contributions of stand characteristics, topography, soil texture and pH value to spatial variations would differ among SOC, TN and TP in forests. To test these hypotheses, we collected soil and floor litter samples from two secondary forests in a subtropical area: a *Choerospondias axillaris* deciduous broadleaved forest and a *Lithocarpus glaber–Cyclobalanopsis glauca* evergreen broadleaved forest. The *C. axillaris* forest was regenerated from secondary succession after firewood collection by the local community was outlawed from the late 1950s, while the *L. glaber–C. glauca* forest was well preserved with less disturbance. The two forests were located in close proximity and had identical climatic conditions and the same parent materials, but consisted of different tree species. The amounts of litterfall and fine root productivity were higher in the *C. axillaris* forest than in the *L. glaber–C. glauca* forest (Guo et al. 2015; Liu et al. 2014), and these affected the nutrient input to the soil. SOC, TN and TP concentrations in the soils and litterfalls were all analyzed. Stand characteristics, topography, soil texture and the pH values of the two forests were also measured. We attempted to: (1) determine how stand characteristics affected spatial variations in SOC, TN and TP concentrations in the subtropical forests; and (2) examine whether the magnitude of the effect of stand characteristics varied among SOC, TN and TP owing to their different cycling characteristics.

Materials and methods

Site and stand description

The study was conducted at the Dashanchong Forest Park (28°23′58″ N to 28°24′58″ N, 113°17′46″ E to 113°19′08″ E; 55–217.4 m above mean sea level) in Changsha County, Hunan Province, China. Soil in this area is designated as well-drained clay loam red soil developed from slate and shale rock, classified as Alliti-Udic Ferrosols in the Chinese Soil Taxonomy, which corresponds to Acrisol in the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB 2006). This region is characterized by a subtropical southeastern monsoon climate, with annual precipitation ranging from 1412 to 1559 mm and an annual mean temperature of 17.3 °C. The mean monthly maximum temperature of 40 °C occurs in July and the mean monthly minimum temperature of −11 °C occurs in January. The forests investigated were stands that originated from secondary succession forests in regions where firewood collection has been outlawed and no other management activities have been carried out since the late 1950s. After decades of afforestation and forest protection, secondary forest vegetations have been developed and preserved, dominated by species that include *L. glaber*, *C. glauca*, *Castanopsis fargesii*, *Pinus massoniana* and *Phyllostachys edulis*.

A 1 ha plot (100 × 100 m) was established in each of the two forests investigated, a *C. axillaris* deciduous broadleaved forest and a *L. glaber–C. glauca* evergreen broadleaved forest. The locations of individual trees were mapped and tree species, diameter at breast height (DBH), height (H) and crown width were recorded within the two forests. When the individual trees with a DBH > 4 cm in the plots were counted, the *C. axillaris* forest had lower stand density, average DBH and H and lower basal area (BA) than the *L. glaber–C. glauca* forest (Table 1). Importance values (IVs) were calculated in an earlier study by Zhao et al. (2013).

Contrasting tree species dominated both forests. The top five dominant species ranked by IV in the *C. axillaris* forest were *C. axillaris*, *Loropetalum chinense*, *Symplocos setchuenensis*, *Vernicia montana* and *Vernicia fordii*, while the top five in the *L. glaber–C. glauca* forest were *L. glaber*, *C. glauca*, *P. massoniana*, *C. axillaris* and *Cleyera japonica*. Stand characteristics of the two forests are presented in Table 1.

Sample collection and chemical analysis

Each of the study plots was further divided into a grid of 100 subplots of 10 × 10 m, and samples were obtained from the center of each subplot between May 25 and June 16 in 2014. Within each sampling subplot, floor litter in 50 × 50 cm areas was collected prior to soil sampling. Subsequently, soil samples were retrieved from the 0–10 cm soil layer and taken to the laboratory to measure SOC, TN and TP concentrations, soil texture and pH values. Soil texture (clay, silt and sand contents) were determined by the pipette method (Gee and Bauder 1986). Soil pH values were measured at a soil-to-water (deionized) ratio of 1:2.5 using an FE20 pH meter

Table 1 Stand density, average diameter at breast height (DBH), average height (H), basal area (BA) and importance value (IV) of the top five tree species and whole stands with DBH > 4 cm in the *Choerospondias axillaris* and *Lithocarpus glaber–Cyclobalanopsis glauca* forests investigated

Forest type	Tree species	Density (stem ha^{-1})	DBH (cm)	H (m)	BA (m^2 ha^{-1})	IV (%)
C. axillaris deciduous broadleaved forest	*C. axillaris*	184	23.3 (4.1–54.1)	15.7 (3.2–34.5)	9.1	26
	Loropetalum chinense	410	5.2 (4.0–14.8)	4.9 (1.6–21.5)	0.9	16
	Symplocos setchuenensis	144	6.4 (4.0–20.3)	5.2 (2.0–8.9)	0.6	7
	Vernicia montana	57	10.4 (4.0–41.8)	9.7 (1.5–23.6)	0.9	5
	Vernicia fordii	44	11.4 (4.2–33.3)	10.0 (3.6–23.5)	0.6	4
	Whole stand	1430	9.2 (4.0–31.6)	7.2 (1.3–34.5)	16.6	100
L. glaber–C. glauca evergreen broadleaved forest	*L. glaber*	586	10.4 (4.0–37.1)	9.6 (2.2–19.5)	6.7	26
	C. glauca	164	12.8 (4.0–34.6)	10.4 (3.8–20.0)	3.0	10
	Pinus massoniana	123	18.0 (7.0–32.2)	14.2 (1.3–20.0)	3.5	10
	C. axillaris	83	19.3 (4.0–46.8)	13.5 (1.8–20.2)	2.9	8
	Cleyera japonica	199	5.9 (4.0–18.2)	5.8 (2.2–16.1)	0.6	78
	Whole stand	1788	11.0 (4.0–46.8)	9.7 (1.2–21.0)	23.7	100

Values in parentheses are ranges of DBH and H

(Mettler Toledo, Shanghai, China). For SOC, TN and TP measurements, soils were manually sorted to visually remove stones, plant roots and litter, and then sieved through a 0.25 mm mesh. SOC concentrations were determined by the $K_2Cr_2O_7/H_2SO_4$ oxidation method. TN concentrations were determined using a semimicro-Kjeldahl method, and TP concentrations were measured by sodium hydroxide (NaOH) fusion and the Mo–Sb colorimetric method. Litter samples collected were oven dried at 65 °C to a constant weight and weighed to determine dry mass.

Data analysis

Descriptive statistics, including maximum value, minimum value, average value, error value and coefficient of variation (CV) of SOC, TN and TP concentrations, were calculated. The differences in SOC, TN and TP concentrations between the two forests were tested by two-way analysis of variance (ANOVA). To improve the precision of the variation function model, outliers were identified using the threshold value method and were replaced with the maximum of the remaining dataset after the outliers were excluded (Tukey 1977). Subsequently, the Kolmogorov–Smirnov (K–S) test was used to examine whether all data conformed to a normal distribution. The data for soil TP concentrations in the *L. glaber–C. glauca* forest showed a high degree of

skew and failed normality tests, so a square root transformation was applied.

Spatial variability of SOC, TN and TP concentrations was determined by geostatistical analysis using GS+ Version 9 software (Gamma Designs Software, Plainville, MI, USA). The geostatistical approach can be used to obtain unbiased estimates and map soil attributes in locations that have not been previously sampled, using relationships between raw data and semivariograms. The latter showed changes in the scatter plot of function values over increases in sample lag. Scatter diagrams could be fitted by four different models, including the exponential model, the spherical model, the Gaussian model and the linear model. Semivariograms use three significant statistical parameters to describe degrees of spatial variation: nugget (C_0), sill ($C_0 + C$) and range (A_0). C_0 represents random variability on a spatial scale, $C_0 + C$ represents the greatest variation in system properties, $C_0/(C_0 + C)$ reflects the magnitude of the random variation in total variations, and A_0 describes the scale of spatial variation (Okin et al. 2008). Variables have spatial correlations within the A_0 scale, whereas there are no spatial correlations beyond the range of A_0. The semivariance (λ) at a given lag (h) is calculated according to the following equation:

$$\lambda(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad (1)$$

where $\lambda(h)$ is the semivariance function value, $N(h)$ is the number of pairs separated by lag (h), $Z(x_i)$ is defined as the x_i point of the Z sample as it relates to spatial location, and $Z(x_i + h)$ is a regionalized variable on the $(x_i + h)$ point.

Based on the fitness of each model, semivariances of SOC, TN and TP concentrations were described by the linear model for the *C. axillaris* forest and by the Gaussian model for the *L. glaber–C. glauca* forest (Table S1). The model selected and the parameters fitted were processed using the kriging procedure to interpolate values for locations that were not sampled. The kriging method is an interpolation method that not only accurately estimates soil properties but also estimates approximated errors and the precision of predicted values for locations that have not been sampled. Spatial distribution maps of SOC, TN and TP concentrations were then generated for each 10×10 m subplot using the predicted interpolation values.

Elevation and convexity for each 10×10 m subplot were also measured. The elevation ranged from 125 to 170 m in the *C. axillaris* forest and from 71 to 128 m in the *L. glaber–C. glauca* forest (Fig. S1). Elevation at a subplot center was determined as the average of the elevations of the four corners of the subplot. Convexity was calculated by subtracting the elevation at a subplot center from the mean elevation of the eight surrounding subplots. For edge subplots, convexity was calculated by determining the elevation of each subplot minus the mean altitude of the surrounding subplots. Stand characteristics included tree species number, stand density, crown coverage, average DBH, height, BA, deciduous proportion, evergreen proportion, conifer proportion, Shannon index, average canopy width per tree and litter biomass. In this study, the data for stand characteristics within a 10×10 m subplot were only determined for trees higher than the average stand height. Based on leaf morphological and phenological traits, trees were grouped into coniferous, deciduous or evergreen broadleaved species. The summed BA of the coniferous, deciduous and evergreen broadleaved species were divided by the total BA of the entire subplot to obtain their relative proportions.

Since there were weak correlations between topography, soil texture and stand characteristics in the two forests (Tables S2 and S3), stepwise linear regression was applied to determine their effects on SOC, TN and TP for the *C. axillaris* and *L. glaber–C. glauca* forests investigated. In the linear regression model, the following variables were included: topography (elevation and convexity), soil pH value and texture (clay, silt and sand) and stand characteristics (tree species number, stand density, crown coverage, average stand DBH, height, BA, conifer proportion, deciduous proportion, evergreen proportion, Shannon index, average canopy width per tree and litter biomass). After application of stepwise linear regression based on Akaike's Information Criterion (de Micheaux et al. 2013), the variables that had significant correlations with SOC, TN and TP were selected as explanatory variables and grouped into topography, soil texture or stand characteristics (Tables S4 and S5). The relative contributions of stand characteristics, topography and soil texture to variations in SOC, TN and TP concentrations in a forest were calculated by dividing the explanatory (or regression) sum of squares (*ESS*) of each factor by the total regression sum of squares (*TSS*) of the variations in the stepwise linear regression. All statistical analyses were conducted using R-3.00 statistical software (R Development Core Team 2009).

Results

Variations in soil SOC, TN and TP concentrations in the two forests

The mean SOC and TN concentrations in the *C. axillaris* forest were significantly lower than those in the *L. glaber–C. glauca* forest, whereas the average TP concentration was significantly higher in the *C. axillaris* forest than in the *L. glaber–C. glauca* forest (Table 2). The CVs of SOC and of TN concentration in the *C. axillaris* forest were 31 % and 38 % lower than those in the *L. glaber–C. glauca* forest, respectively. However, the CV of soil TP concentration exhibited a reverse trend, being 43 % higher in the *C. axillaris* forest (24 %) than that in the *L. glaber–C. glauca* forest (17 %).

Spatial variations in soil SOC, TN and TP concentrations

Geostatistical analyses revealed that the selected models had R^2 values ranging from 0.654 to 0.997 (Fig. 1). In the *C. axillaris* forest, spatial autocorrelation was weak for SOC and TN concentration but was moderate for TP concentration, as indicated by the $C_0/(C_0 + C)$ ratios that

Table 2 Minimum, maximum, mean, standard deviation (SD) and coefficient of variation (CV) of soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) concentrations at a soil depth of 0–10 cm in the *C. axillaris* and *L. glaber–C. glauca* forests investigated

Stand types	Items	Mean	Minimum	Maximum	SD	CV (%)	Kolmogorov–Smirnov test	Data transformation
C. axillaris deciduous broadleaved forest	SOC (g kg^{-1})	20.07***	10.46	35.84	5.43	27	0.59	
	TN (g kg^{-1})	1.62***	1.14	2.84	0.34	21	0.15	
	TP (g kg^{-1})	0.29***	0.14	0.54	0.07	24	0.47	
L. glaber–C. glauca evergreen broadleaved forest	SOC (g kg^{-1})	23.98	9.63	62.09	8.49	35	0.31	
	TN (g kg^{-1})	1.90	0.65	4.29	0.64	34	0.19	
	TP (g kg^{-1})	0.27	0.18	0.41	0.04	17	0.03	0.09

A total of 100 samples were obtained from each forest stand. Three asterisks (***) indicate that the differences between the two forests are significant at $p < 0.001$

were larger than 0.750 for SOC and TN and between 0.250 and 0.750 for TP. In the *L. glaber–C. glauca* forest, SOC, TN and TP concentrations showed moderate spatial autocorrelations, with $C_0/(C_0 + C)$ ratios ranging from 0.250 for TP to 0.500 for SOC.

Spatial autocorrelation ranges in SOC, TN and TP concentrations varied between the two forests (Fig. 1). In the *C. axillaris* forest, SOC concentrations had a spatial autocorrelation range of 53.0 m, which was greater than that in the *L. glaber–C. glauca* forest (23.7 m). Differences in autocorrelation ranges were small for TN and TP between the *C. axillaris* forest (53.0 m for TN and 53.0 m for TP) and the *L. glaber–C. glauca* forest (60.8 m for TN and 69.1 m for TP).
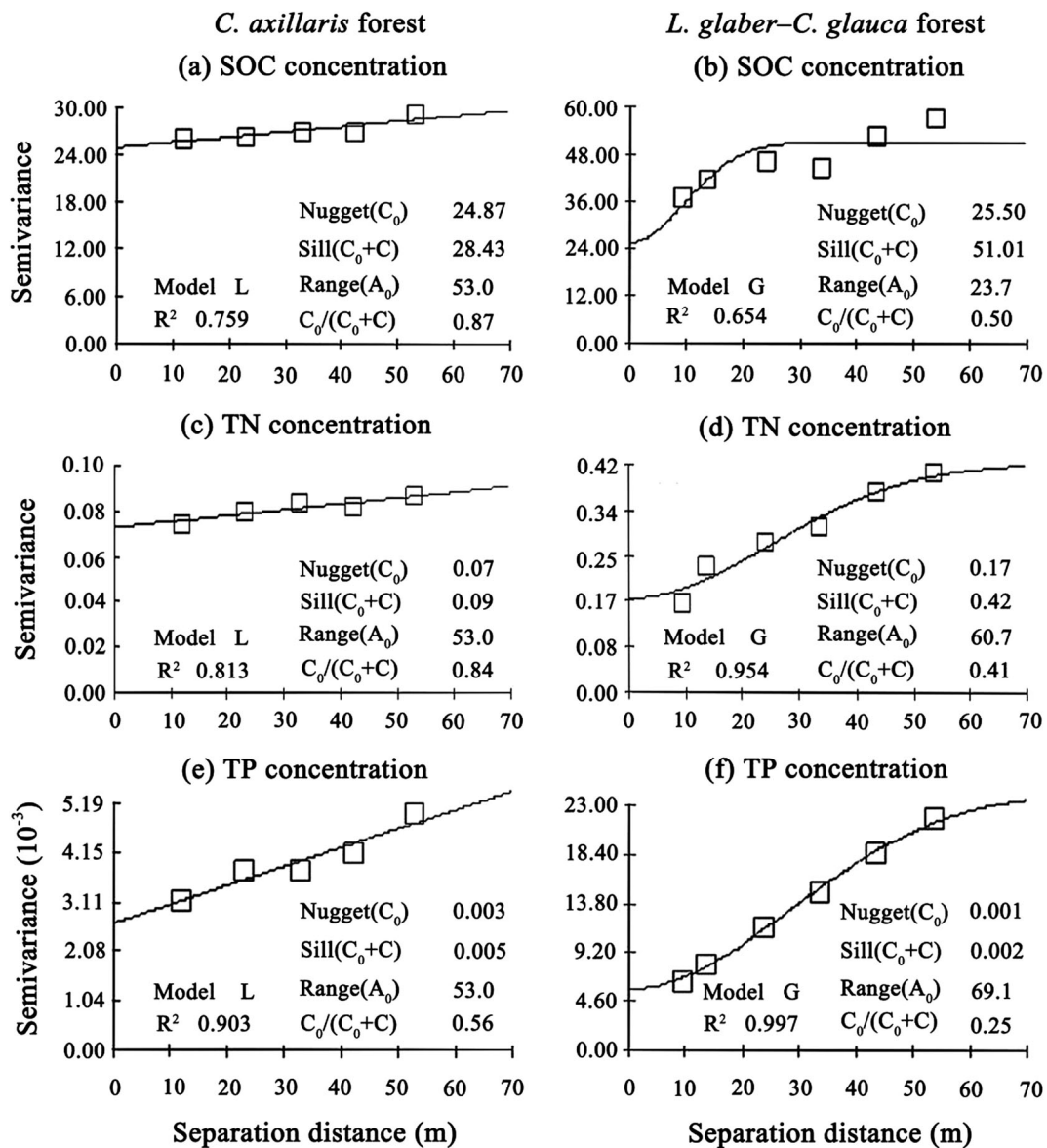
Spatial distribution maps for SOC, TN and TP concentrations were generated for the two forests using GS+ Version 9 software (Fig. 2). As shown, SOC, TN and TP concentrations exhibited patchy patterns for both forests. Patch sizes (ranges) for SOC, for example, in the *C. axillaris* forest (53.0 m) were more than twice as large as those in the *L. glaber–C. glauca* forest (23.7 m). The patch sizes of TN and TP were found to be larger in the *L. glaber–C. glauca* forest, which were 1.2 and 1.3 times as large as those in the *C. axillaris* forest, respectively. High SOC, TN and TP concentrations were observed in valleys in the *L. glaber–C. glauca* forest, whereas in the *C. axillaris* forest, high SOC, TN and TP concentrations were found in subplots comprised of trees with large DBH values.

Contributions of stand characteristics to variations in SOC, TN and TP concentrations

Stepwise regression analysis revealed that stand characteristics, together with topography and soil texture, were able to explain 20 % and 28 % of SOC variations in the *C. axillaris* and *L. glaber–C. glauca* forests, respectively (Fig. 3). Stand characteristics contributed the most to SOC variations in both forests, contributing 8 % in the *C. axillaris* forest and 21 % in the *L. glaber–C. glauca* forest (Fig. 3). However, topography contributed the least to variation in SOC, only 5 % in the *C. axillaris* forest. Soil texture made a modest contribution to variation in SOC, which was 7 % in the *C. axillaris* forest and 8 % in the *L. glaber–C. glauca* forest. All selected factors varied greatly in terms of their contributions to SOC variations in the two forests. Elevation, sand content, species number and DBH were significant explanatory variables in the *C. axillaris* forest (Table S2), whereas silt content, litter biomass, BA and canopy width were significantly related to variations in SOC concentration in the *L. glaber–C. glauca* forest (Table S3).

Up to 43 % and 40 % of the variation in soil TN in the *C. axillaris* and *L. glaber–C. glauca* forests, respectively, were explained by the selected factors, of which stand characteristics explained about 10 % of TN variation in both forests (Fig. 3). Topography contributed to 11 % and 10 % of TN variation in the *C. axillaris* and *L. glaber–C. glauca* forests, respectively (Fig. 3). Soil texture was the greatest contributor to variation in TN (Fig. 3). However, the total contributions of soil texture to TN variation were similar in the two forests (Fig. 3). Elevation, clay content, sand content and DBH were significantly related to variations in TN concentration in the *C. axillaris* forest (Table S2), while significant relationships were detected between soil TN
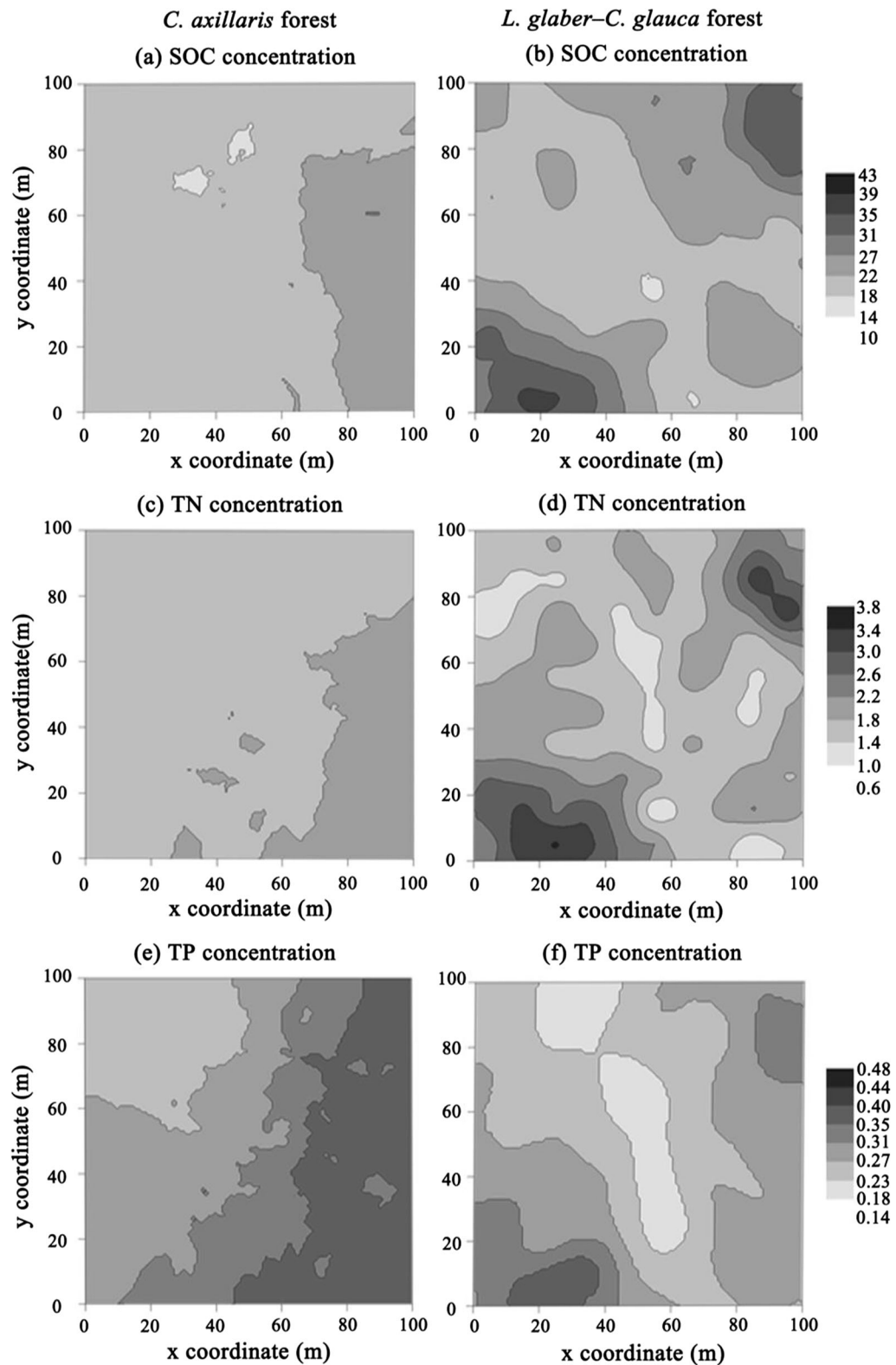
C. axillaris forest

(a) SOC concentration

Nugget(C_0) 24.87
Sill(C_0+C) 28.43
Model L   Range(A_0) 53.0
R^2 0.759 C_0/(C_0+C) 0.87

(c) TN concentration

Nugget(C_0) 0.07
Sill(C_0+C) 0.09
Model L   Range(A_0) 53.0
R^2 0.813 C_0/(C_0+C) 0.84

(e) TP concentration

Nugget(C_0) 0.003
Sill(C_0+C) 0.005
Model L   Range(A_0) 53.0
R^2 0.903 C_0/(C_0+C) 0.56

Separation distance (m)

L. glaber–C. glauca forest

(b) SOC concentration

Nugget(C_0) 25.50
Sill(C_0+C) 51.01
Model G   Range(A_0) 23.7
R^2 0.654 C_0/(C_0+C) 0.50

(d) TN concentration

Nugget(C_0) 0.17
Sill(C_0+C) 0.42
Model G   Range(A_0) 60.7
R^2 0.954 C_0/(C_0+C) 0.41

(f) TP concentration

Nugget(C_0) 0.001
Sill(C_0+C) 0.002
Model G   Range(A_0) 69.1
R^2 0.997 C_0/(C_0+C) 0.25

Separation distance (m)

Fig. 1 Semivariograms of soil organic carbon (SOC) (**a**), total nitrogen (TN) (**c**) and total phosphorus (TP) (**e**) concentrations in *Choerospondias axillaris* forest and semivariograms of soil organic carbon (SOC) (**b**), total nitrogen (TN) (**d**) and total phosphorus (TP) (**f**) concentrations in *Lithocarpus glaber–Cyclobalanopsis glauca* forest. A summary of the semivariogram model parameters

for SOC, TN and TP in the two forests is provided under the curve. The selected models for semivariogram analysis (L = linear model; G = Gaussian model) are indicated. The proportion of structural variation C_0/(C_0 + C) was used as an index of the magnitude of spatial dependence

concentration and convexity, sand content, BA and canopy width in the *L. glaber–C. glauca* forest (Table S3).
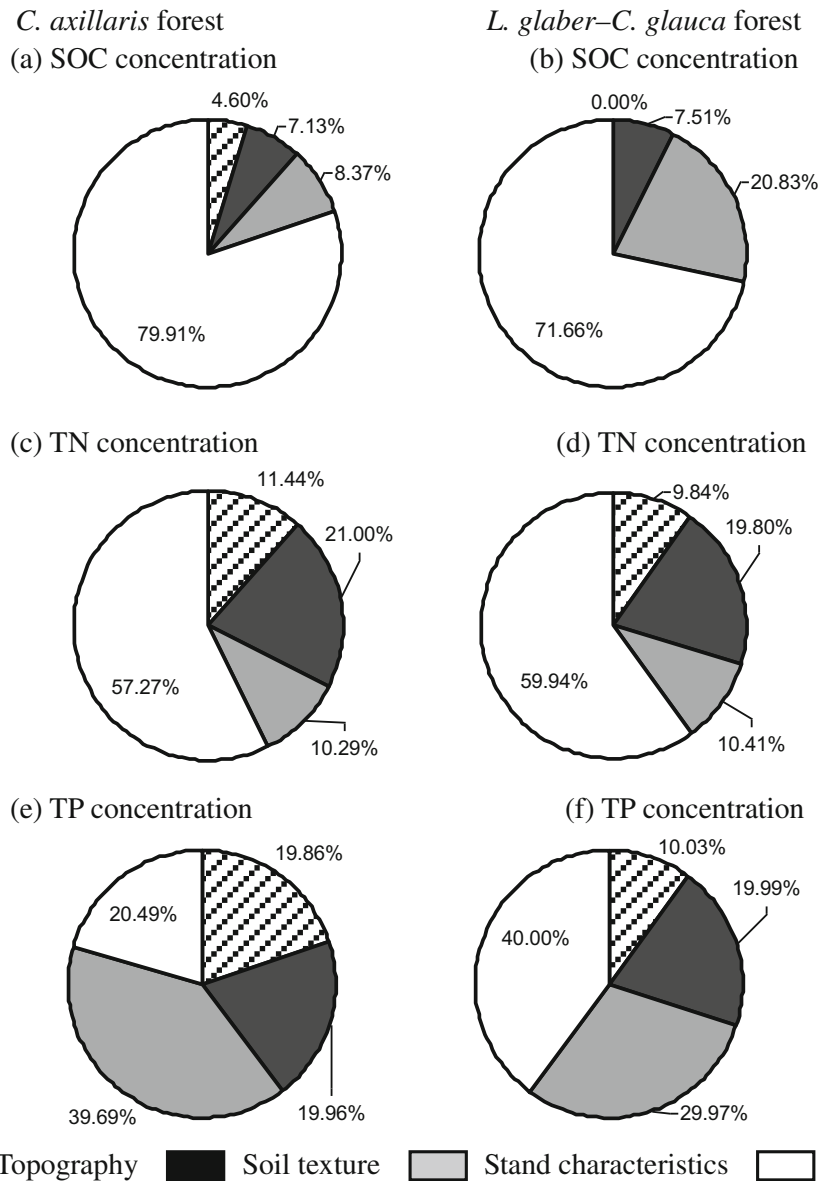
The contributions of stand characteristics, topography and soil texture to variations in TP were 80 % in the *C. axillaris* forest and 60 % in the *L. glaber–C. glauca* forest (Fig. 3). Among the

factors investigated, stand characteristics exhibited a greater contribution to variations in TP than topography and soil texture. The contribution of stand characteristics to variations in TP concentration was higher in the *C. axillaris* forest (40 %) than in the *L. glaber–C. glauca* forest (30 %) (Fig. 3). The contributions of topography and soil

Fig. 2 Spatial heterogeneity map of soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) concentrations in the *C. axillaris* and *L. glaber–C. glauca* forests investigated

C. axillaris forest
(a) SOC concentration

4.60%
7.13%
8.37%
79.91%

L. glaber–C. glauca forest
(b) SOC concentration

0.00%
7.51%
20.83%
71.66%

(c) TN concentration

11.44%
21.00%
57.27%
10.29%

(d) TN concentration

9.84%
19.80%
59.94%
10.41%

(e) TP concentration

19.86%
20.49%
39.69%
19.96%

(f) TP concentration

10.03%
19.99%
40.00%
29.97%

Topography   Soil texture   Stand characteristics   Unexplained

Fig. 3 Relative contributions of topography, soil texture and stand characteristics to variations in soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) concentrations in the *C. axillaris* and *L. glaber–C. glauca* forests investigated

texture were 20 % and 20 % in the *C. axillaris* forest and 10 % and 20 % in the *L. glaber–C. glauca* forest. Elevation, sand content, evergreen proportion and DBH were the significant factors that related to TP concentration in the *C. axillaris* forest (Table S2). However, in the *L. glaber–C. glauca* forest, regression analysis indicated that elevation, clay content, silt content, stem, BA and canopy width were significantly related to TP concentration (Table S3).

Discussion

Effects of stand characteristics on variations in soil SOC, TN and TP concentrations

Average SOC and TN concentrations were significant lower but average TP concentration was significantly higher in the *C. axillaris* forest than those in the *L. glaber–C. glauca* forest (Table 2). This supported our first hypothesis that stand characteristics affected

soil SOC, TN and TP concentrations. Our results were consistent with the study by Ding et al. (2015) that SOC and soil N concentrations were significantly higher in an evergreen broadleaved forest than in a deciduous broadleaved forest in subtropical areas. This could be explained by the fact that evergreen broadleaved forest accumulated more soil organic matter (Ding et al. 2015). It was reported that *L. glaber–C. glauca* forest accumulated more litter and had a lower decomposition rate of leaf litter (Guo et al. 2015) and fine roots (Tong et al. 2012) compared to *C. axillaris* forest. However, the result that soil TP concentrations were higher in the *C. axillaris* forest than in the *L. glaber–C. glauca* forest differs from that of Ding et al. (2015). It could be attributed to more P input (litterfall and fine root productivity) from trees and rapid litter turnover in the *C. axillaris* forest (Guo et al. 2015; Liu et al. 2014; Tong et al. 2012). In contrast, Yang et al. (2014) found relatively higher SOC and N but slightly lower P in a deciduous broadleaved forest than in an evergreen broadleaved forest. Average SOC concentration observed for broadleaved forests in this study was lower than that reported by Zhang et al. (2014) for broadleaved forest in a tropical area, but TN and TP concentrations were much higher for broadleaved forest in our study than those found by Zhang et al. (2014). These differences between the studies are due to the fact that Yang et al. (2014) studied a planted forest and Zhang et al. (2014) studied a tropical area, while the forests in our study were naturally regenerated in a subtropical area.

The *C. axillaris* forest exhibited lower variations (CV) in SOC and TN concentrations but higher variations in TP concentration compared to the *L. glaber–C. glauca* forest (Table 2). The variations were comparable to the results obtained in temperate forests (Wang et al. 2015) and in tropical forests (Robert et al. 2007; Xia et al. 2015). Moreover, the two forests investigated in this study showed different spatial variation patterns. Autocorrelations for SOC, TN and TP concentrations in the *C. axillaris* forest were weak or moderate and showed large autocorrelation ranges (Fig. 1) and large grain spatial distribution (Fig. 2). In contrast, the *L. glaber–C. glauca* forest showed moderate autocorrelation for SOC, TN and TP concentrations, but autocorrelation ranges and spatial grain varied among SOC, TN and TP concentrations. Stepwise linear regression analysis (Tables S2 and S3) showed that the variations in SOC, TN and TP in the forests investigated were

positively and significantly correlated with stand characteristics, including BA, DBH and canopy width. This indicates a potential influence of stand characteristics on the spatial heterogeneity of soil nutrients in these forests (Hirobe et al. 2001). A previous study also found influences of BA and the canopy structure of trees on spatial variations in soil nutrients in temperate forest soil (Yuan et al. 2013). Canopy structure may affect the temperature and moisture content of forest floor soil, which are important factors affecting the litter decomposition processes; thus, the tree canopy may influence spatial variations in soil nutrients (Sariyildiz 2008). Xia et al. (2015) observed that the distribution of giant (large DBH) trees was related to nutrient conditions and that differences in the DBH of trees may result in different inputs of litterfall to the soil surface and help create spatial variations in soil nutrient concentrations.

Contributions of stand characteristics to soil nutrients in the two forests

Although stand characteristics were important factors affecting spatial variability in SOC, TN and TP concentrations, their ability to explain spatial variations differed for SOC, TN and TP concentrations, which was higher for TP in comparison to SOC and TN in both forests. This supported our second hypothesis that the magnitude of the effect of stand characteristics on spatial variations varied among SOC, TN and TP concentrations. This could have been due to different cycling characteristics among nutrient elements, which were more open for C and N cycles, whereas they were relatively closed for P. Such differences in the magnitude of the effect of stand characteristics on different cycling elements were also observed in tropical forests at similar or smaller study scales. Xia et al. (2015) reported a different effect of stand characteristics (litterfall nutrients) on fine-scale spatial variations of N and P within a 1 ha tropical forest. Changes in vegetation cover were shown to affect the magnitudes of spatial variations among SOC, N and P (Blair, 2005). It is worth noting that the majority of total P in soils is inorganic P, and this proportion of P should not be affected by stand characteristics, suggesting that the latter may affect mainly spatial variations in available P in forest soils.

In addition, other factors may be related to variations in SOC, TN and TP concentrations. In our study, the contribution of topography to spatial variations was

higher for TN and TP concentrations than for SOC concentration. Topography is known to affect local microclimates, litter decomposition and the leaching of soil surface nutrients (Baldeck et al. 2012; Xia et al. 2015). However, these processes may result in different impacts among SOC, TN and TP concentrations. Different studies have addressed the influence of topography on variations in soil SOC and nutrient concentrations. For example, Xia et al. (2015) found a possible link between N (NO$_3$-N), but not P, and topographic gradients.

In contrast to SOC and TP, soil texture showed the highest contribution to variations in TN, supporting the finding of Rodríguez et al. (2009) that soil texture determined the magnitude of the plant effect on spatial variations in forest soil N concentration. However, soil texture contributed similarly to SOC, TN and TP variations in the two forests investigated (Tables S2 and S3; Fig. 3), indicating that the strength of the influence of soil texture on spatial variations in SOC, TN and TP concentrations did not vary among different forests. This could be attributed to the fact that soil texture was relatively stable (Rodríguez et al. 2009) and resistant to modification by stand characteristics over short time periods (Augusto et al. 2002; Hagen-Thorn et al. 2004; Pohl et al. 2009). Our findings extended previous general results in temperate or tropical forests to subtropical forests, which showed that SOC and soil nutrient variations in forests were highly dependent on stand characteristics. However, influences from abiotic factors, including topography and soil texture as well as the cycling characteristics of elements, were also important (Gruba et al. 2015; Paluch and Gruba 2010; Schulp et al. 2008; Xia et al. 2015).

In this study, the high proportion of unexplained variations in SOC concentration could be ascribed to the fact that potentially important factors, such as soil respiration, were not taken into account. Topsoil carbon can easily diffuse into the atmosphere as CO$_2$ via soil respiration, and such loss of carbon to the atmosphere can be strongly affected by the quantity and quality of litter inputs to soils (Fanin et al. 2011; Vesterdal et al. 2012). The composition of different species contributing to litter production was found to be highly diverse in both forests. Therefore, variations in litter quantity and quality may have led to spatially high variations in soil respiration (Guo et al. 2015), which may consequently have caused a spatial variation in SOC concentration. Subtropical forests in southern China are undergoing increasing N deposition (Chen and Mulder 2007). This increased N deposition may exceed the forest soil N retention capacity and thereby cause substantial leaching of N to surface runoff (Akselsson et al. 2010). The heterogeneous composition of tree species may interact with soil conditions to influence N leaching processes, which, in our study, resulted in an unexplained variation in TN concentration between the two forests investigated. Stand characteristics, topography and soil texture in this study were better able to explain the variations in soil TP concentration than those of SOC and TN concentrations. This is probably because the P was relatively stable and could not be lost via processes such as soil CO$_2$ respiration or N leaching.

Conclusions

The *C. axillaris* deciduous broadleaved forest investigated in our study exhibited lower average concentrations and coefficients of variation of SOC and TN than the *L. glaber–C. glauca* evergreen broadleaved forest studied, whereas TP showed a reverse trend. Spatial autocorrelations of SOC, TN and TP concentrations were either weak or moderate in the *C. axillaris* forest but were moderate in the *L. glaber–C. glauca* forest. The different patterns of SOC, TN and TP in the two forests reflected the more diverse tree species and complex structure of the *L. glaber–C. glauca* forest compared to the *C. axillaris* forest. In addition, topography and soil texture were related to variations in SOC, TN and TP. Stand characteristics contributed the most to spatial variations in SOC and TP, while soil texture made the largest contribution to variations in TN. Topography contributed the least to variations in SOC, TN and TP. The contribution of stand characteristics differed for SOC, TN and TP due to their different cycling characteristics.

Author contributions Idea and study design: WX; data collection and analysis: FJ, YZ, SO, PL and XD, with support from WX and XF; manuscript writing: FJ, XW, WX and CP.

References

Akselsson C, Belyazid S, Hellsten S, Klarqvist M, Pihl-Karlsson G, Karlsson P-E, Lundin L (2010) Assessing the risk of N leaching from forest soils across a steep N deposition gradient in Sweden. Environ Pollut 158:3588–3595

Augusto L, Ranger J, Binkley D, Rothe A (2002) Impact of several common tree species of European temperate forests on soil fertility. Ann For Sci 59:233–253

Bae J, Ryu Y (2015) Land use and land cover changes explain spatial and temporal variations of the soil organic carbon stocks in a constructed urban park. Landsc Urban Plan 136: 57–67

Baldeck CA, Harms KE, Yavitt JB et al (2012) Soil resources and topography shape local tree community structure in tropical forests. Proc R Soc B Biol Sci 280:2012–2532

Blair BC (2005) Fire effects on the spatial patterns of soil resources in a Nicaraguan wet tropical forest. J Trop Ecol 21:435–444

Chen XY, Mulder J (2007) Atmospheric deposition of nitrogen at five subtropical forested sites in south China. Sci Total Environ 378:317–330

Cremer M, Kern NV, Prietzel J (2016) Soil organic carbon and nitrogen stocks under pure and mixed stands of European beech, Douglas fir and Norway spruce. For Ecol Manag 367: 30–40

De Micheaux PF, Drouilhet R, Liquet B (2013) The R software: fundamentals of programming and statistical analysis. Springer, New York, pp 487–489

Development Core Team R (2009) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Ding JJ, Zhang YG, Wang MM, Sun X, Cong J, Deng Y, Lu H, Yuan T, Nostrand JDV, Li DQ, Zhou JZ, Yang YF (2015) Soil organic matter quantity and quality shape microbial community compositions of subtropical broadleaved forests. Mol Ecol 24:5175–5185

Fanin N, Hättenschwiler S, Barantal S, Schimann H, Fromin N (2011) Does variability in litter quality determine soil microbial respiration in an Amazonian rainforest? Soil Biol Biochem 43:1014–1022

Fantappiè M, Abate GL, Costantini EAC (2011) The influence of climate change on the soil organic carbon content in Italy from 1961 to 2008. Geomorphology 135:343–352

Garten CT, Kand S, Brice DJ, Schadt CW, Zhou JZ (2007) Variability in soil properties at different spatial scales (1 m–1km) in a deciduous forest ecosystem. Soil Biol Biochem 39: 2621–2627

Gee GW, Bauder JW (1986) Particle-size analysis. In: Klute A (ed) Methods of soil analysis. Part 1, 2nd edn. Agron. Monogr. 9. ASA and SSSA, Madison, pp 383–411

Gonzalez OJ, Zak DR (1994) Geostatistical analysis of soil properties in a secondary tropical dry forest, St. Lucia, West Indies. Plant Soil 163:45–54

Gruba P, Socha J, Błońska E, Lasota J (2015) Effect of variable soil texture, metal saturation of soil organic matter (SOM) and tree species composition on spatial distribution of SOM in forest soils in Poland. Sci Total Environ 521–522:90–100

Guo J, Yu LH, Fang X, Xiang WH, Deng XW, Lu X (2015) Litter production and turnover in four types of subtropical forests in China. Acta Ecol Sin 35:4668–4677 (in Chinese with English abstract)

Hagen-Thorn A, Callesen I, Armolaitis K, Nihlgård B (2004) The impact of six European tree species on the chemistry of mineral topsoil in forest plantations on former agricultural land. For Ecol Manag 195:373–384

Hirobe M, Ohte N, Karasawa N, Zhang G, Wang L, Yoshikawa K (2001) Plant species effect on the spatial patterns of soil properties in the Mu-us desert ecosystem, Inner Mongolia, China. Plant Soil 234:195–205

Hobbie SE (1992) Effects of plant species on nutrient cycling. Trends Ecol Evol 7:336–339

Hoffmanna U, Hoffmann T, Jurasinskic G, Glatzel S, Kuhn NJ (2014) Assessing the spatial variability of soil organic carbon stocks in an alpine setting (Grindelwald, Swiss Alps). Geoderma 232–234:270–283

IUSS (International Union of Soil Sciences) Working Group WRB (2006) "World Reference Base for Soil Resources 2006," World Soil Resources Reports No. 103, FAO, Rome

Liu C, Xiang WH, Lei PF, Deng XW, Tian DL, Fang X, Peng CH (2014) Standing fine root mass and production in four Chinese subtropical forests along a succession and species diversity gradient. Plant Soil 376:445–459

Liu SJ, Zhang W, Wang KL, Pan FJ, Yang S, Shu SY (2015) Factors controlling accumulation of soil organic carbon along vegetation succession in a typical karst region in Southwest China. Sci Total Environ 521–522:52–58

Luizão RCC, Luizão FJ, Paiva RQ, Monteiro TF, Sousa LS, Kruijt B (2004) Variation of carbon and nitrogen cycling processes along a topographic gradient in a central Amazonian forest. Plant Soil 10:592–600

Okin GS, Mladenov N, Wang L, Cassel D, Caylor KK, Ringrose S, Macko SA (2008) Spatial patterns of soil nutrients in two southern African savannas. J Geophys Res 113:G02011. doi:10.1029/2007JG000584

Paluch JG, Gruba P (2010) Relationships between local stand density and local species composition and nutrient content in the topsoil of pure and mixed stands of silver fir (*Abies alba* Mill.). Eur J For Res 129:509–520

Pohl M, Alig D, Körner C, Rixen C (2009) Higher plant diversity enhances soil stability in disturbed alpine ecosystems. Plant Soil 324:91–102

Robert J, Dalling JW, Harms KE, Yavitt JB, Stallard RF, Mirobello M, Hubbell SP, Valencia R, Navarrete Y, Vallejo M, Foster RB (2007) Soil nutrients influence spatial distributions of tropical tree species. Proc Natl Acad Sci U S A 104:864–869

Rodríguez A, Durán J, Fernández-Palacios JM, Gallardo A (2009) Spatial variability of soil properties under *Pinus canariensis* canopy in two contrasting soil textures. Plant Soil 322:139–150

Sariyildiz T (2008) Effects of gap-size classes on long-term litter decomposition rates of beech, oak and chestnut species at high elevations in northeast Turkey. Ecosystems 11:841–853

Schleuß PM, Heitkamp F, Leuschner C, Fender AC, Jungkunst HF (2014) Higher subsoil carbon storage in species-rich than species-poor temperate forests. Environ Res Lett 9:014007

Schöttelndreier M, Falkengren-Grerup U (1999) Plant induced alteration in the rhizosphere and the utilization of soil heterogeneity. Plant Soil 209:297–309

Schulp CJE, Nabuurs GJ, Verburg PH, de Waal RW (2008) Effect of tree species on carbon stocks in forest floor and mineral

soil and implications for soil carbon inventories. For Ecol Manag 256:482–490

Sheikh MA, Kumar M, Bussmann RW (2009) Altitudinal variation in soil organic carbon stock in coniferous subtropical and broadleaf temperate forests in Garhwal Himalaya. Carbon Balance Manag 4:1–6

Tong J, Xiang WH, Liu C, Lei PF, Tian DL, Deng XW, Peng CH (2012) Tree species effects on fine root decomposition and nitrogen release in subtropical forests in southern China. Plant Ecolog Divers 5:323–331

Tukey JW (1977) Exploratory data analysis. Addison-Wesley Publishing Co, Reading

Vesterdal L, Elberling B, Christinansen JR, Callesen I, Schmidt IK (2012) Soil respiration and rates of soil carbon turnover differ among six common European tree species. For Ecol Manag 264:185–196

Wang LX, Mou PP, Huang JH, Wang J (2007) Spatial heterogeneity of soil nitrogen in a subtropical forest in China. Plant Soil 295:137–150

Wang H, Liu SR, Wang JX, Shi ZM, Lu LH, Zeng J, Ming AG, Tang JX, Yu HL (2013) Effects of tree species mixture on soil organic carbon stocks and greenhouse gas fluxes in subtropical plantations in China. For Ecol Manag 300:4–13

Wang JM, Yang RX, Bai ZK (2015) Spatial variability and sampling optimization of soil organic carbon and total nitrogen for Minesoils of the Loess Plateau using geostatistics. Ecol Eng 82:159–164

Winowiecki L, Vågen TG, Huising J (2015) Effects of land cover on ecosystem services in Tanzania: A spatial assessment of soil organic carbon. Geoderma 263:274–283

Xia SW, Chen J, Schaefer D, Detto M (2015) Scale-dependent soil macronutrient heterogeneity reveals effects of litterfall in a tropical rainforest. Plant Soil 391:51–61

Xia SW, Chen J, Schaefer D, Goodale UM (2016) Effect of topography and litterfall input on fine-scale patch consistency of soil chemical properties in a tropical rainforest. Plant Soil 404:385–398

Yang JK, Zhang JJ, Yu HY, Cheng JW, Miao LH (2014) Community composition and cellulose activity of cellulolytic bacteria from forest soils planted with broad-leaved deciduous and evergreen trees. Appl Microbiol Biotechnol 98: 1449–1458

Yuan ZQ, Gazol A, Lin F, Ye J, Shi S, Wang XG, Wang M, Hao ZQ (2013) Soil organic carbon in an old-growth temperate forest: spatial pattern, determinants and bias in its quantification. Geoderma 195–196:48–55

Zhang JY, Cheng KW, Zang RG, Ding Y (2014) Environmental filtering of species with different functional traits into plant assemblages across a tropical coniferous–broadleaved forest ecotone. Plant Soil 380:361–374

Zhao L, Xiang W, Li J, Deng X, Liu C (2013) Floristic composition, structure and phytogeographic characteristics in a *Lithocarpus glaber–Cyclobalanopsis glauca* forest community in the subtropical region. Sci Silvae Sin 49:10–17 (in Chinese with English abstract)