Ecological Engineering 67 (2014) 171–181

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Long-term effects of different land use types on C, N, and P stoichiometry and storage in subtropical ecosystems: A case study in China

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ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 6 January 2014
Accepted 24 March 2014

Keywords:
Land use
Ecological stoichiometry
Carbon
Nitrogen
Phosphorus
Carbon threshold

ABSTRACT

Land use changes and associative management practices can alter the biogeochemical cycling and ecological stoichiometry of carbon (C), nitrogen (N), and phosphorous (P) in ecosystems, but much remains to be clarified. This study explored the long-term effects of different land use types on C, N, and P stoichiometry and storage in a subtropical region, southern China. Scientists based at the Qianyanzhou Forest Experimental Station studied the characteristics of C, N, and P content and their corresponding ratios for six different land use types, ranging from farmland to native forests. Results showed that C, N, and P content declined with increasing soil depth. C:N ratios for surface soils generally grew over time but declined in deeper soil layers while both C:P and N:P ratios declined significantly over time. Compared to forest soils, considerably higher C and N density and storage were observed in orchard and farmland soils, although other soil types investigated showed even higher. Lastly, C density and storage threshold was ascertained for forest soils.

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1. Introduction

Government sponsored reforestation projects have a great effect on altering land use pattern distribution in subtropical regions in China through afforestation initiatives or the establishment of plantation forests on abandoned agricultural land (Cao et al., 2007, 2010, 2011). Land use changes has shown that such initiatives have a significant impact on soil carbon (C), nitrogen (N), and phosphorus (P) cycling and their associative storage capacities (Houghton, 1999; Scott et al., 2006; Cao et al., 2009; Jiao et al., 2012). A byproduct of reforestation is a significant increase in plant C stocks and belowground C accumulation in mineral soil (Billings, 2006; Scott et al., 2006). Whether or not reforestation can promote a limitless increase in ecosystem C storage is poorly understood and remains disputed among researchers (Gao et al., 2012a, 2013a,b).

N and P cycling are tightly coupled to C cycling in ecosystems, primarily through effects related to ecosystem C primary production (Luo et al., 2006; Gao et al., 2013a,b). Land use change and related management practices can alter C, N, and P biogeochemical cycling by the effect it incurs on soil properties. Many studies have reported that soil properties differ considerably between plantations and forests (Liao et al., 2012). For example, Chen et al. (2005) and Nsabimana et al. (2008) reported that soil pH and soil C and N concentrations are lower than those found in natural forests. Furthermore, Behera and Sahani (2003) and Lemma et al. (2006) reasoned that soil bulk density is higher in plantations than in natural forests. Other studies dispute these conclusions, suggesting that soil pH as well as soil C and N concentrations increase while soil bulk density decreases due to reforestation (Wall and Hytönen, 2005; Pibumrung et al., 2008).

Outcomes of land use effects on soil properties are primarily the result of changes in plant type. Different plant types can effect soil C, N, and P through detritus and litter decomposition (which in turn depend on the chemical and physical composition of living plants), root secretion and N fixation, soil mineralization, and contributions to soil ecosystems from resident animals, insects, and microorganisms (Montagnini et al., 1993; Roggy et al., 1999; Warren and Zou, 2002; Hobbie et al., 2006). Furthermore, different plant species differ in their capacity to utilize and capture

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http://dx.doi.org/10.1016/j.ecoleng.2014.03.013
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Table 1
Change in land use patterns between 1980 and 1997 in QFES (Li and Yuan, 2001).

		Cropland	Orchard	Forest	Grassland	Water	Wasteland	Others
1980	Area (ha)	19.85	3.32	0.88	0.14	7.35	172.63	2.77
	%	9.72	1.63	0.43	0.07	3.60	83.20	1.35
1990	Area (ha)	16.98	37.96	121.77	2.71	10.89	10.58	3.28
	%	8.32	18.59	59.64	1.33	5.33	5.18	1.61
1997	Area (ha)	15.95	37.16	122.73	1.22	10.86	10.53	3.60
	%	7.81	18.20	60.11	0.60	5.32	5.16	1.76

essential resources supplied by C, N, and P (Wang et al., 2013; Wu et al., 2012). Agronomists and biologists continue to study the effects various species have on surface soil C and N dynamics. These effects can have both short-term consequences, which are evident after a single growing season (Binkley et al., 2000; Giardina et al., 2001; Rhoades et al., 2001), as well as long-term consequences (Russell et al., 1998, 2004, 2007).

Sartori et al. (2006) suggested that land use history, soil and plant type as well as the associative management practices utilized were closely related to soil C accumulation and nutrient dynamics. In addition, determining present and past land use change is critical when ascertaining terrestrial ecosystem C sources or sinks. It is therefore important for researchers to estimate the current and potential effect of land use change on soil C storage (Lal, 1998, 2003). At the same time, comparable estimates in differences between C, N, and P density for forested and agricultural soils are necessary to understand the impact that past reforestation and future land use changes on C, N, and P stocks.

The native soil of the Qianyanzhou Forest Experimental Station (QFES) is typical of the subtropical red soil found in China. Since QFES was established in 1983, the station has undergone substantial land use changes on three separate occasions, resulting from government-sponsored reforestation initiatives. This study investigated changes in C, N, and P density and storage in QFES between 2002 and 2012 after extensive land use changes had taken place. The objectives of this study were to better understand the relationship between land use and C, N, and P density and storage, and to demonstrate whether C sequestration thresholds will result in consequence to long-term land use changes driven by reforestation initiatives.

2. Materials and methods

2.1. Study area

This study was carried out at QFES, located in Taihe County, Jiangxi Province, southern China (long 115°04′13″ E, lat 26°44′48″ N) (Fig. 1a). The station is supported by and operates under the aegis of the Chinese Academy of Sciences (CAS). The terrain has a slope between 10° and 30°. Height above mean sea level varies between 20 and 60 m for which the highest point in the study area was 115.5 m above mean sea level. The climate of the region can be characterized as subtropical and moist with an average annual rainfall of 1361 mm and a mean annual air temperature of 18.6 °C. The highest measured temperature since the 1980s was 39.5 °C and the lowest was −5.8 °C.

The red soil characteristic of the region consists of red sandstone and mudstone and is classed as an Udic Ferrisol. Other local soil types include paddy soil (an Anthrosol), fluvo-aquic soils, and meadow soils. Within this region, clay content is 350–400 $\mathrm{g\,kg^{-1}}$; organic matter content in surface soil is 10–15 $\mathrm{g\,kg^{-1}}$; the degree of cultivated soil is 20 $\mathrm{g\,kg^{-1}}$; pH value is 4.5–5.2. The clay mineral mainly was kaolinite, accounting for 80–85% of total weight, and the clay content of SiO_2/Al_2O_3 is 2.0–2.4 $\mathrm{g\,kg^{-1}}$.

Table 2
Changes in the six main land use patterns between 2002 and 2012 in QFES.

Land use type	Area (ha)	
	2002	2012
Broadleaved coniferous mixed forest (mixed forest)	10.18	11.13
Fir forest	14.05	7.04
Slash pine forest	39.88	39.66
Masson pine forest	32.20	45.65
Orchard	34.36	33.73
Farmland	15.95	14.39

2.2. Land use change history

The study area is typical of the subtropical, hilly, red soil terrain found in much of Jiangxi Province. It is characterized by low hills, hill terraces, and valley floodplains. Total QFES area is 207.96 ha. Since QFES was established in 1983, investigations related to land use change have been carried out on three separate occasions: in 1983, 1990, and 1997. The research site belongs to the middle subtropical evergreen broadleaf zone. Primary forests have almost disappeared in the region due to deforestation and conversion to agriculture. However, farmland and heavily eroded wasteland have been replanted with fruit orchards and forest plantations (fir and pine forests).

As Table 1 shows, wasteland accounted for 83.20% of the total area before 1983. After undergoing ten years of land management, QFES land use structure has fundamentally changed. Forested area increased from 0.88 to 121.77 ha, accounting for 59.64% of the total area, while orchards increased from 3.32 to 37.96 ha, accounting for 18.59% of the total area. Cropland underwent a slow decrease in land area while grassland experienced a slight increase over a 14-year period. Areas of other land use types account for a very small proportion of change, being dispersed throughout QFES.

After 1997, major QFES land use and land cover types remained relatively constant. Table 2 shows changes that took place in the six major land use types between 2002 and 2012 while Fig. 1b shows the main land use patterns in 2012. The total area of the six major land use types in 2002 and 2012 were 146.62 and 151.6 ha, respectively, accounting for 70.50% and 72.89% of the total area, respectively (Table 2).

2.3. Soil sampling protocols

Soil sampling was initially carried out between May 20 and June 5 2002. The six major land use types were selected for which two soil profiles were taken from each, which were also referenced by Wang et al. (2004) for their earlier study. Given that results from 2002 were specified as the average values of two soil profiles, differences between the 2002 mean values and the 2012 mean values could only be compared since a finer-textured ANOVA analysis comparing results from different soil levels was not possible due to the previous method employed. Sampling for the present study was carried out between May 30 and June 1 2012. Soil was sampled at three depths: 0–15 cm, 15–30 cm, and 30–60 cm. For each land

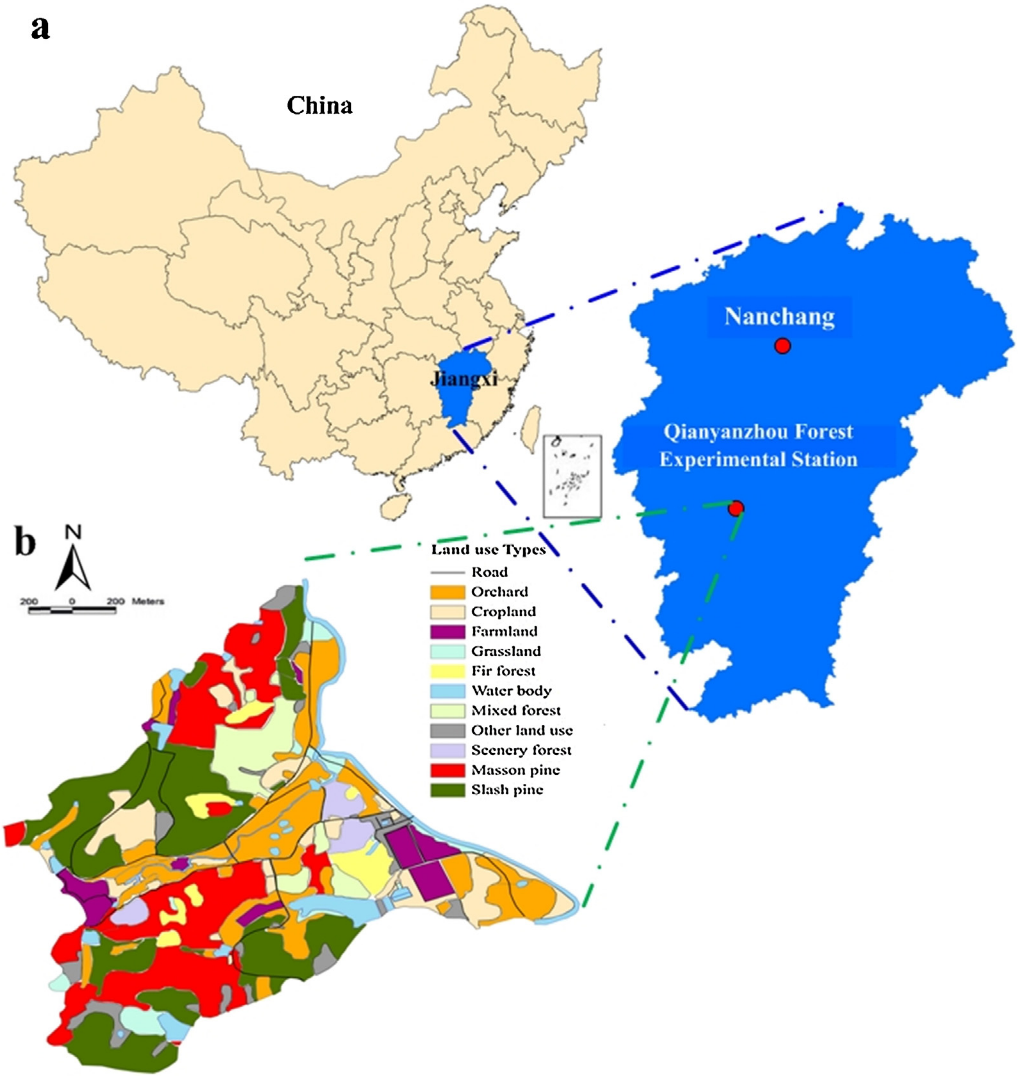

Fig. 1. Location of QFES (a) and land use patterns in 2012 (b).

use type, four replicates for each of the three depths were obtained for soil sampling. Each soil sample was collected by excavating soil from a 1 m radius circle at the specific soil level until a net weight of 1 kg of wet soil was collected. Soil samples were then stored in a refrigerator until they could be processed for chemical analysis.

Sampling of the six land use types in 2012 was carried out at the following locations: (1) mixed forest (long 115°03′53″ E, lat 26°44′45″ N); (2) fir forest (long 115°03′54″ E, lat 26°44′45″ N); (3) slash pine forest (long 115°03′39″ E, lat 26°44′51″ N); (4) masson pine forest (long 115°03′39″ E, lat 26°44′53″ N); (5) orchard (long 115°03′49″ E, lat 26°44′44″ N); and (6) farmland (long 115°03′46″ E, lat 26°44′40″ N). Locations of soil profiles for 2002, here referenced from Wang et al. (2004) or from the Chinese Ecosystem Research Network (CERN) database (www.cern.ac.cn), were as follows: (1) mixed forest (long 115°03′54.9″ E, lat 26°44′44.0″ N); (2) fir forest (long 115°03′58.8″ E, lat 26°44′46.7″ N); (3) slash pine forest (long 115°03′50.8″ E, lat 26°44′43.8″ N); (4) masson pine forest (long 115°03′36.7″ E, lat 26°44′28.7″ N); (5) orchard (long 115°03′48.1″ E, lat 26°44′45.6″ N); and (6) farmland (long 115°03′48.5″ E, lat 26°44′51.4″ N).

Physical and chemical data obtained by this study were then compared to results from soil samples gathered between May and June 2002 (obtained from the CERN database). QFES, being a CAS project, is a member of CERN. All previously collected data for the region was accessed by this means. This included data on social and economic conditions, land use, environment, and soil composition.

2.4. Laboratory methods

Soil organic carbon (SOC) was determined using the $K_2Cr_2O_7$ volumetric dilution heating method (Nelson and Sommers, 1982); total nitrogen (TN) was determined using the Kjeldahl procedure (Gallaher et al., 1976); total phosphorus (TP) was determined using $H_2SO_4 + HClO_4$ digestion (Olsen and Sommers, 1982); soil bulk density was determined by the core method; soil pH was measured using the potentiometric method with a soil–water ratio of 1:2.5(w/v).

2.5. Calculation of C, N, and P density and storage

C, N, and P density were calculated as follows:

$$D = \sum_{l=1}^{n} C_i \times d_i \times b_i \qquad (1)$$

$$S = D \times A \qquad (2)$$

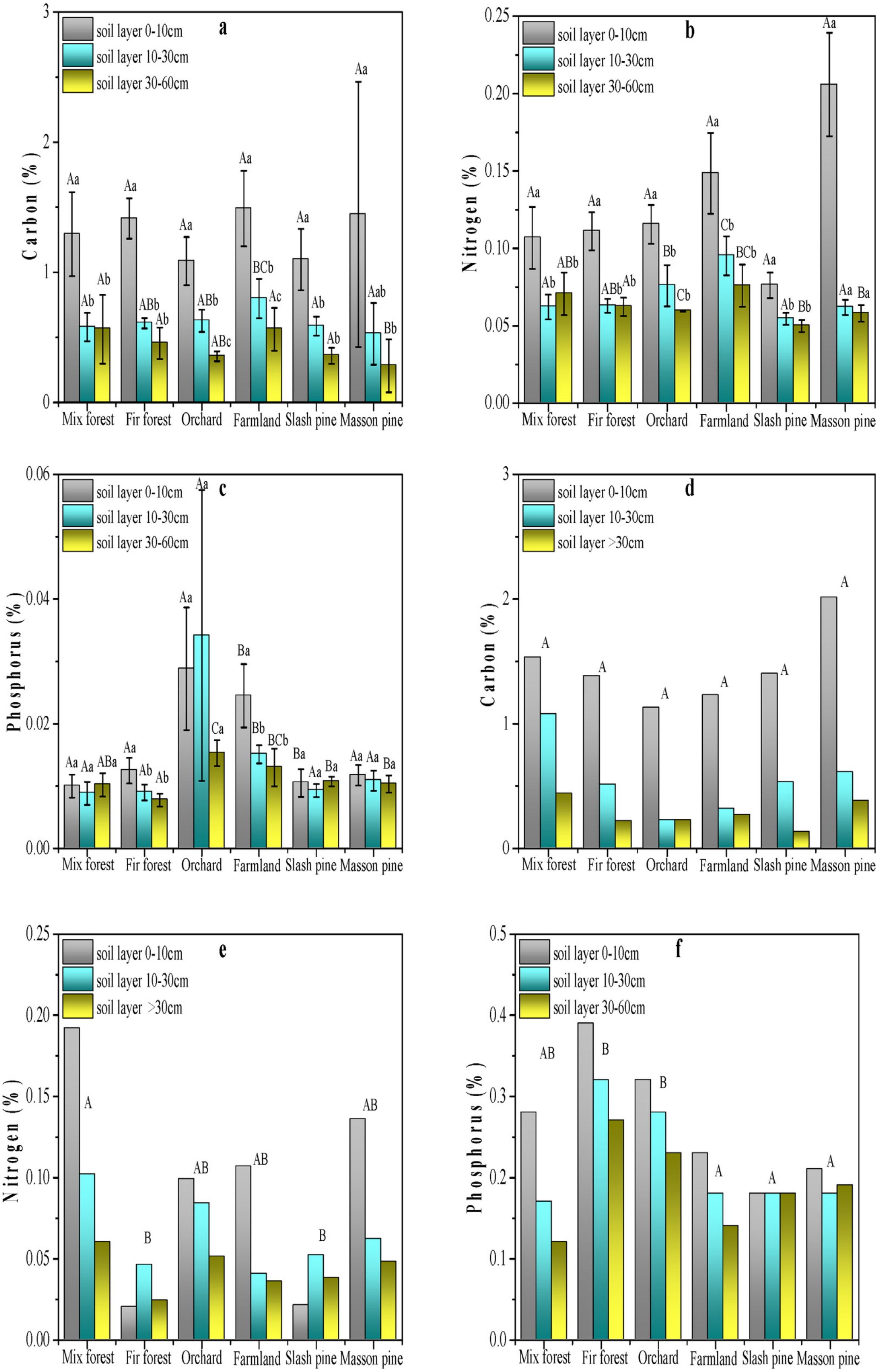

Fig. 2. Changes in C, N, and P for the land use types and soil depths between 2002 and 2012. Figures a, b, and c are changes in C, N, and P in 2012, respectively, and d, e, and f are changes in C, N, and P in 2002, respectively. *Note*: Different capital letters denote significant differences in land use types while different lowercase letters denote significant differences in soil depths under a significance level of $P < 0.05$.

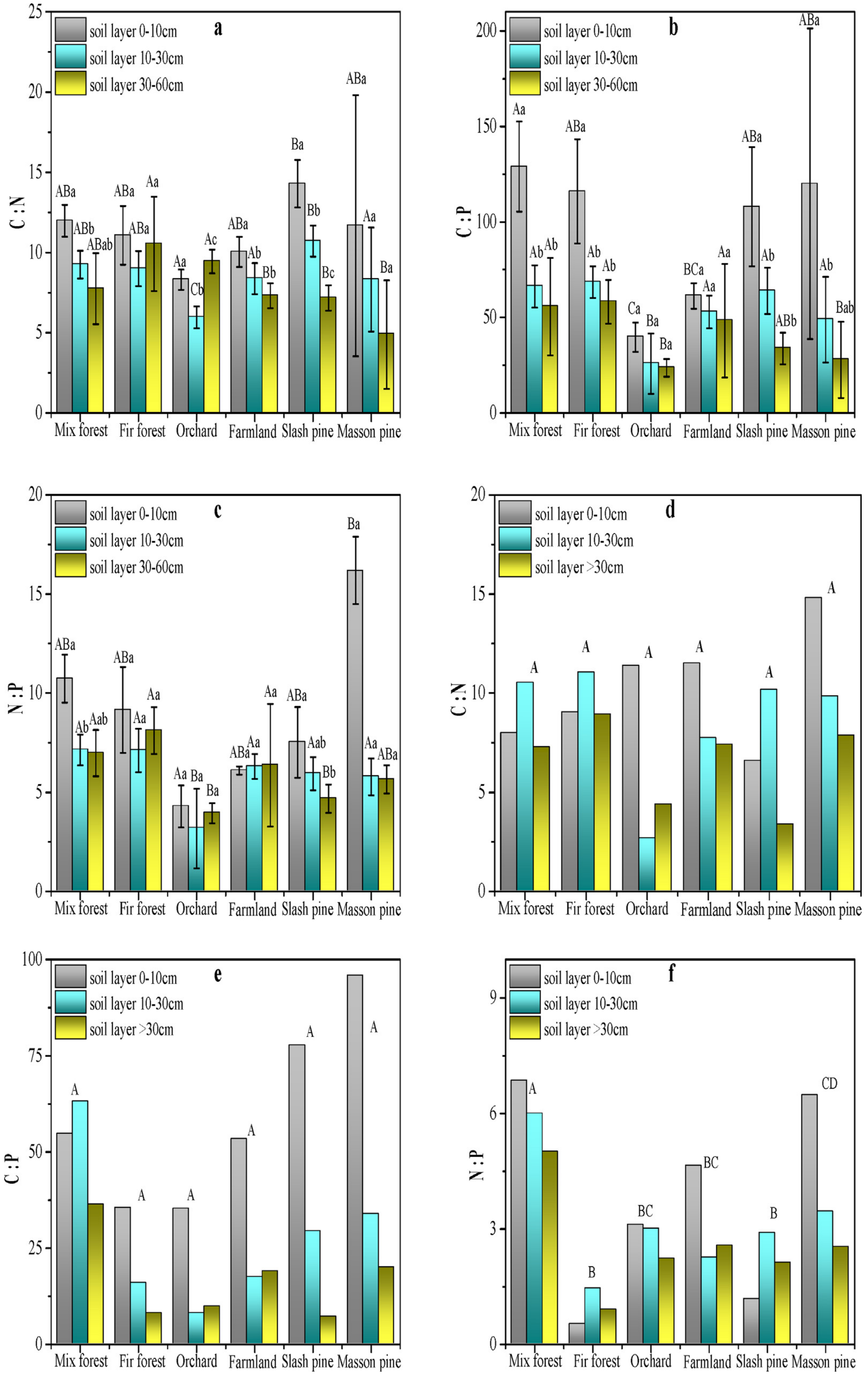

Fig. 3. Changes in C:N, C:P, and N:P ratios for land use types and soil depths between 2002 and 2012. Figures a, b, and c provide 2012 ratios while d, e, and f provide 2002 ratios. *Note*: Different capital letters denote significant differences in land use types while different lowercase letters denote significant differences in soil depths under a significance level of $P < 0.05$.

where i is the soil layer in the vertical section; C_i is the mean content of C, N, and P in soil layer i; d_i is the sample depth from the topsoil downward; b_i is the bulk density (g cm^{-3}) in soil layer i; D is the C, N, and P density (t hm^{-2}); A is the area of each plant sample (hm^{-2}); S is C, N, and P storage. Soil taken below a 60 cm depth was considered to be equivalent to soil taken precisely at a 60 cm soil depth.

2.6. Statistical analysis

Concentrations of C, N, and P for each soil sample were used to determine the C:N, C:P, and N:P ratios. C, N, and P stoichiometry was calculated as a mass ratio. Differences between C:N, C:P, and N:P ratios were found in several soil layers and were evaluated using one-way analysis of variance (ANOVA), followed by the least significant difference (LSD) test. Statistical analyses were carried out using SPSS 13.0 software (SPSS Inc., Chicago, IL).

3. Results

3.1. Changes in C, N, and P

Significant differences were found between samples taken at various depths and in various habitats (Fig. 2). Results also showed differences in C, N, and P content between samples taken in 2002 and those taken in 2012. Fig. 2a shows that C deceased as soil depth increased. C content in surface soil was highest for masson pine. However, soil samples taken from the 30–60 cm layer in those same masson pine forests exhibited the lowest C content of any of the six land use types investigated. The mean value of C content (the average values from all soil depths) for farmland was higher than the mean values for any of the other land use types investigated. In general, N content decreased as soil depth increased, as it was also observed for C (Fig. 2b). N content found in soil layers spanning between 10 and 60 cm was significantly higher in farmland than in the other soils investigated.

P content also varied for different soil depths and for different land use types (Fig. 2c). P content under farmland, fir, and masson pine forests decreased with increasing soil depth, whereas P content for the 30–60 cm soil layer under mixed and slash pine forests was higher than the 10–30 cm soil layer. The mean value of P for all soil layers was significantly higher under the orchard land use type than under the other habitats investigated. The highest P content in orchard soil samples was found in the 15–30 cm layer.

C, N, and P content for the 2002 soil samples were significantly higher than for the 2012 samples. P in particular decreased between 2002 and 2012. As Fig. 2d shows, surface soil C content under five land use types exhibited only small decreases between 2002 and 2012. Farmland, however, exhibited a small increase. Nevertheless, soil C content between 10 and 60 cm increased for these same five land use types with the exception of farmland once again. N content in surface soil decreased between 2002 and 2012. The decrease was greatest for the mixed forest land type. In both sets of samples (2002 and 2012), N increased as soil depth increased. For 2002, this increase was highest for the 10–30 cm soil layer for both fir and slash pine forests. For the 2012 results, however, this effect was most pronounced in samples from masson pine. N content between 0 and 30 cm decreased between 2002 and 2012 but increased for the 30–60 cm soil layer. P content in 2002 soil samples under all land use types generally decreased as soil depth increased. P showed significant decreases for all soil layers and land use types between 2002 and 2012 (Fig. 2f).

3.2. C, N, and P stoichiometry

As Fig. 3a shows, the C:N ratio under all land use types was significantly higher in surface soil than in bottom soil. However, orchard and farmland ratios were lower (Fig. 3a). The ratio between C and N generally declined with increasing soil depth. The exceptions were the fir C:N ratio and that the 30–60 cm orchard soil layer was higher than the 10–30 cm orchard soil layer. C:P ratios predictably declined with increasing soil depth (Fig. 3b). The C:P ratio for surface soil was lower for orchard and farmland than for forested areas. It was also found that C:P ratio variation between soil layers was highest for masson pine. Moreover, the N:P ratio for orchard and farmland soils changed only insignificantly with soil depth, whereas N:P ratios for forested soils declined as soil depth increased (Fig. 3c). Additionally, the N:P ratio in surface soils was higher than in bottom soils. This variation was greatest in samples taken for masson pine.

The 2002 C:N, C:P, and N:P ratios for the different land use types were all lower than those measured in 2012. Variations in ratios at different soil depths also changed over time (Fig. 3d–f). In 2002, the highest C:N ratio was found not in surface soil but in the deep soil layer. For example, the C:N ratio for mixed and fir forests was higher for the 10–30 cm soil layer (Fig. 3d). The C:N ratio was similar for orchard and farmland compared to the other land use types (when compared to 2012 results). All C:P ratios under different land use types for 2002 were below 100. Differences in C:P ratios between surface and bottom soils were also significant, except under the mixed forest land type (Fig. 3e). The N:P ratio was lower for the fir forest than for the other land use types investigated, and variation in the N:P ratio was not always highest in surface soils (Fig. 3f). Compared to 2012 results, orchard and farmland N:P ratios were not lower than the other habitats investigated.

3.3. Changes in C, N, and P density and storage

As Table 3 shows, results related to C density and storage differed for different land use types between 2002 and 2012. Increases in C density were highest for the orchard and farmland, and although mixed and masson pine forest C density exhibited only insignificant decreases, increases were observed in fir and slash pine forests. For both years of investigation, net C sequestration was significantly higher for orchard and farmland than for forested areas. Changes in N density and storage paralleled those of C. In the decade between 2002 and 2012, N density and storage increased for land use types. Mixed forests were the only exception. Farmland exhibited higher increases on N density and storage than any other land use type. Between 2002 and 2012, P density and storage decreased for all land use types. This decrease was highest for slash and masson pine forests.

4. Discussion

4.1. Effects of land use change on soil C, N, and P

Through the course of what developed into a long-term experiment between 2002 and 2012, land use was found to be a critical factor in determining soil C, N, and P change following afforestation initiatives. This may be due to the determining factor of plant species in relation to soil organic matter decomposition and ecosystem nutrient recycling (Hooper and Vitousek, 1997; Wardle et al., 1997). Both SOC and nutrient content are primarily dependent on decomposition rates driven by microorganisms in that a close relationship exists between soil microorganisms and plant species (Van der Heijden et al., 1998). C content was higher for masson pine than

Table 3
Changes in soil C, N, and P density and storage for each land use type between 2002 and 2012.

		Land use					
		Mixed forest	Fir forest	Slash pine forest	Masson pine forest	Orchard	Farmland
C density (kg m^{-2})	2002	7.5 ± 1.7	4.1 ± 0.7	3.4 ± 1.0	5.8 ± 1.0	4.6 ± 0.3	5.8 ± 0.2
	2012	7.2 ± 1.6	6.3 ± 1.2	5.2 ± 1.3	4.4 ± 0.8	7.1 ± 0.4	11.5 ± 0.3
N density (kg m^{-2})	2002	0.91 ± 0.21	0.32 ± 0.05	0.46 ± 0.10	0.63 ± 0.11	0.93 ± 0.05	0.71 ± 0.02
	2012	0.83 ± 0.18	0.75 ± 0.14	0.61 ± 0.14	0.77 ± 0.12	1.02 ± 0.05	1.44 ± 0.03
P density (kg m^{-2})	2002	0.16 ± 0.04	0.32 ± 0.06	0.21 ± 0.05	0.22 ± 0.03	0.37 ± 0.02	0.26 ± 0.01
	2012	0.11 ± 0.03	0.10 ± 0.02	0.12 ± 0.02	0.12 ± 0.02	0.30 ± 0.02	0.24 ± 0.01
C storage (×10^5 kg)	2002	76.4 ± 17.8	57.6 ± 10.0	134.1 ± 41.3	186.9 ± 33.1	157. 8 ± 8.9	92.5 ± 3.3
	2012	80.0 ± 18.0	44.3 ± 8.3	206.8 ± 52.6	202.2 ± 37.0	239.7 ± 12.7	164.9 ± 4.0
N storage (×10^5 kg)	2002	9.3 ± 2.1	4.4 ± 0.8	18.2 ± 3.9	20.4 ± 3.4	31. 8 ± 1.7	11.3 ± 0.3
	2012	9.2 ± 2.0	5.2 ± 1.0	24.0 ± 5.6	35.0 ± 5.6	34.3 ± 1.8	20.7 ± 0.4
P storage (×10^5 kg)	2002	1.7 ± 0.4	4.6 ± 0.9	8.3 ± 1.8	7.0 ± 1.0	12.7 ± 0.7	4.2 ± 0.1
	2012	1. 3 ± 0.04	0.7 ± 0.02	4. 8 ± 0.04	5.5 ± 0.02	10.2 ± 0.03	3.5 ± 0.01

for slash pine forests. This can be explained by the fact that soil C accretion strengthens under the effect of afforestation in relatively dry areas but only promotes insignificant increasing effects in soil C in wetter environments (Jackson et al., 2002).

In the present study, land use change and cropland age noticeably affected soil N content. Oelmann et al. (2011a) also reported that due to land use conversion, different plant species would have a different impact on N availability and induced organic matter accumulation. Soil P content significantly declined over time in this study, being higher in farmland and orchard soils than in forested soils. This may be attributable to the fact that soil P available to plants is extremely low in forested soils, which is dependent on interactions with iron (Fe) and aluminum (Al) and the ability of pine mycorrhizae to obtain P from insoluble forms (Oelmann et al., 2011b). Moreover, P availability in soil changes over time due to periodic nutrient uptake from forest soils and the regular application of P fertilizers to agricultural lands. C, N, and P content in soil changes with soil depth under different land use types. This is because microorganism driven decomposition primarily occurs in surface soil and decomposition rates depend on temperature and precipitation, resulting in a large P aggregate percentage on the soil surface (no deeper than 30 cm), which is likely to interact with root redistribution through exudation and acquisition (Gao et al., 2009, 2010).

4.2. *Impact on C, N, and P stoichiometry*

For this study, the C:N ratio for surface soils grew over time while the C:N ratio for soil samples taken at greater depths declined. This may be the result of the extensive forest plantation initiatives that had taken place in the study area. N content decreased as soil depth increased, but N increased along with increasing C. This is because an increase in N facilitates the buildup of C in soils, increasing the overall rate of nutrient cycling (Su and Zhao, 2003; Yuan et al., 2012). A reduction in the soil C:N ratio could alter soil stoichiometric relationships and disrupt the balance between soil C and N cycling in farmland compared to forest soils. It is reasonable to assume that the C:N ratio is generally higher in forest soil than in adjacent agricultural soil because the former retains a higher organic matter content and because greater nutrient absorption takes place through plant roots. In agricultural soils, cultivation and agricultural management practices lead to SOC losses to the atmosphere (Lal, 2002). This may be another reason for the lower C:N ratio found in orchard and farmland soils compared to forest soils. Another reason is erosion. Rainfall induced erosion is a serious problem in southern China, leading to NO_3-N leaching (Gao et al., 2012b). N would consequently accumulate in bottom soils, which are less exposed to erosion. Hence, the C:N ratio would decline as soil depth increased.

C:P and N:P ratios for both 2002 and 2012 were generally lower in samples taken from orchard and farmland soils than in the forested soils. This may be a consequence of anthropogenic N deposition, resulting in the occurrence of associative N:P ratio shifts in forests. Denslow et al. (1987) reported that limited P availability can potentially limit growth in mature forests, and soil P in southern China is known to be limited due to the serious erosional losses that have taken place. Furthermore, P cannot be as easily resupplied compared to N, which can be introduced by N-fixing plants. That leaves decomposition of organic P as one of the primary natural sources of plant-available P (Meason et al., 2009; Kritzler and Johnson, 2010). Orchard and farmland soils can be resupplied with P by the application of fertilizers and manures, whereas forest soils

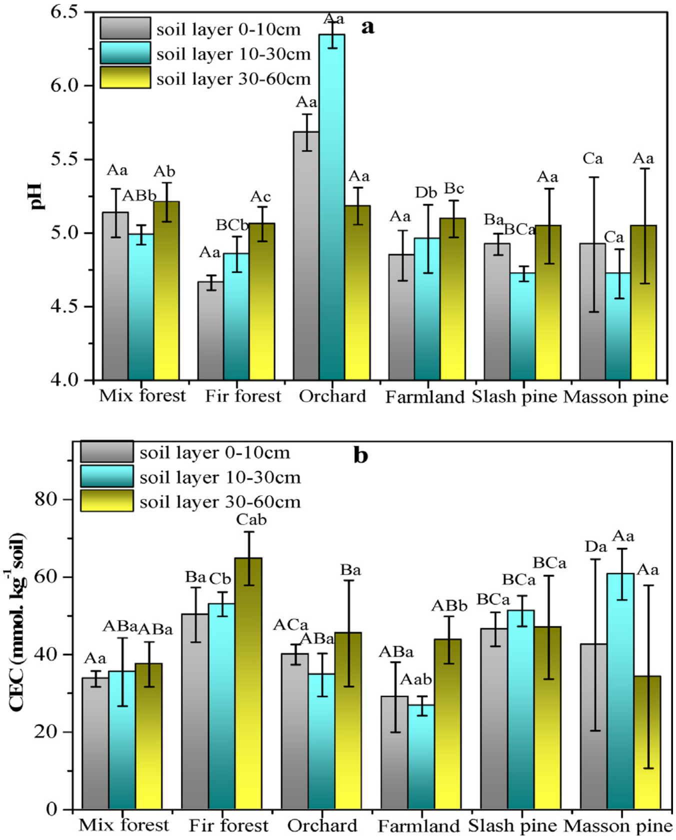

Fig. 4. Changes in pH (a) and CEC (b) for the several habitats and soil depths, 2012 only. *Note*: different capital letters are significantly different from habitats; different lowercase letters are significantly different from soil depths; the significance level is $P < 0.05$.

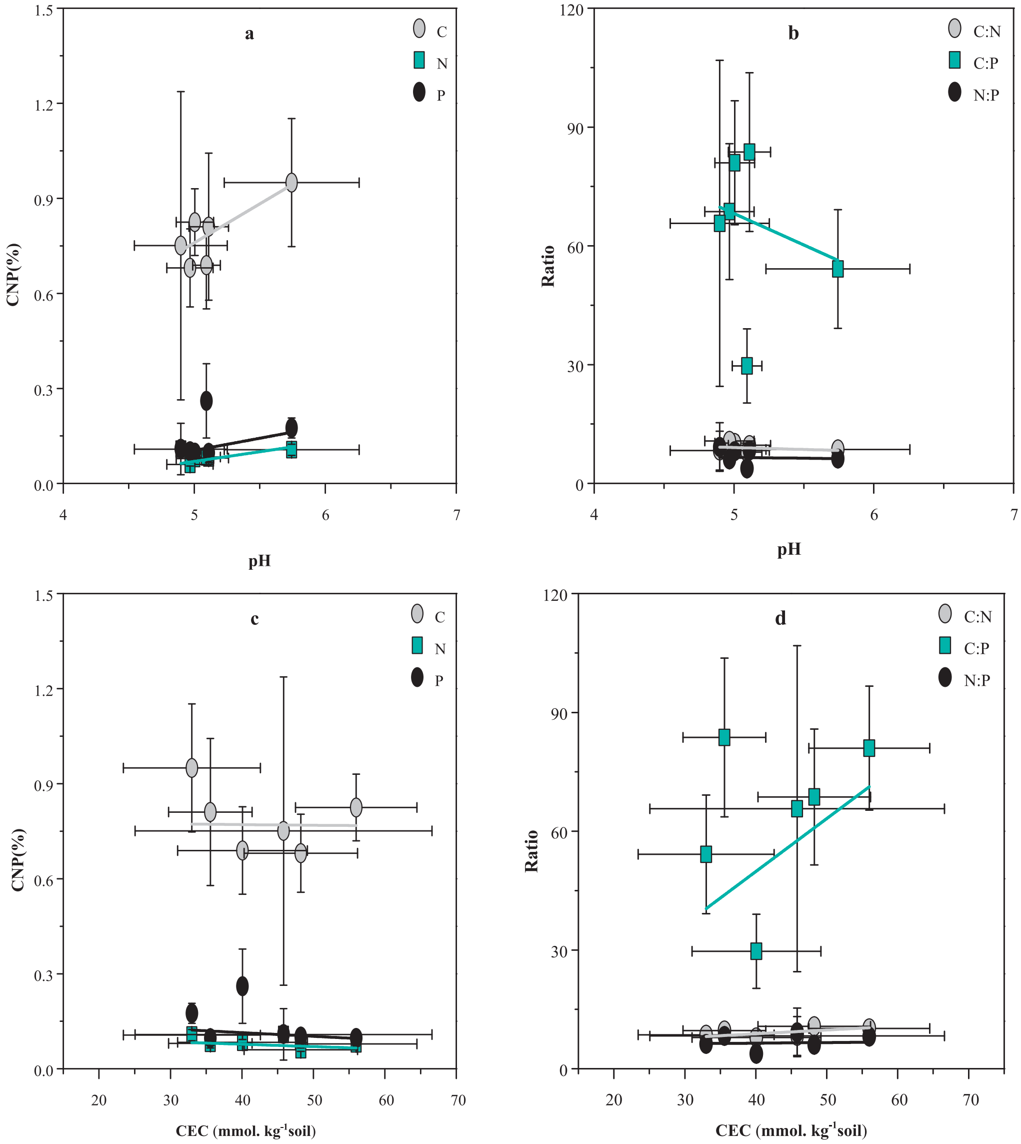

Fig. 5. Analysis of pH and mean C, N, and P content for the various habitats (a) pH and C, N, and P stoichiometry for the various habitats; (b) CEC and mean C, N, and P content for the various habitats; (c) CEC and mean C, N, and P stoichiometry for the various habitats (d).

are resupplied with P almost entirely from the weathering of parent material, which takes place at very slow rates.

4.3. Impact on C, N, and P density and storage

SOC density and storage can vary greatly over time due to changes in environmental conditions (Wang et al., 2004). Given that changes in land use tend to be stable, C and N density and storage between 2002 and 2012 gradually increased in the study area, being highest for orchard and farmland soils, but P deceased for all land use types investigated. These results are in opposition to a report by Lal (2002) who said that land use changes from natural to agricultural ecosystems would result in C pool losses between 30% and 50%. Martin et al. (2010) also reported that the amount of C loss from soil was primarily due to changes in land use type. This could be related to historical land usages and soil properties. As land use changed from cropland to farmland in 1997, more nutrients were input to satisfy crop growth. Thus, during the early stage, farmland and orchards exhibited rapid increases in C and N density and storage. In addition, the red soil typical of QFES aggregates stably, so a reduction in soil tillage and cultivation would also lead to a decline in C and N loss. It should be noted that P is always the primary limiting factor in southern China soils due to P absorption and sorption.

4.4. Effect of soil pH and CEC capacity on soil C, N, and P

Finzi et al. (1998) noted that the C and N content of forest floor soils was correlated with soil pH. Amonette et al. (2004) explained that soil pH below 5 would inhibit humification, which would affect soil C sequestration. Soil pH is also a major factor influencing the species composition of ground vegetation in forest soils (Wilson et al., 2001); species composition would affect the C and N content of decaying vegetation. The current study found that soil pH was generally lower in the surface layer samples than in the samples from deeper soil layers. Forest soil pH was generally below 5 at the surface and gradually increased above 5 as soil depth increased (Fig. 4a). Soil pH was significantly higher in the orchard samples than in the samples from other habitats. Low soil pH can negatively affect nutrient cycling and C sequestration; however, the extent of the effect varies from species to species. Species can in their turn alter soil pH because their litter, decomposed, augments and affects soil (Augusto et al., 2002). Because forest litter is generally more acid (though there is great variation between species) the surface soil in forests is generally more acid than soil from deeper layers (Challinor, 1968). This explains both variation in forest surface soils, and their characteristic low pH.

Rhoades and Binkley (1996) reported that soil pH decline under N_2-fixing species was caused by greater acidification of the exchange complex than that seen under non-N_2-fixing species. Krishnaswamy and Richter (2002) argue that pH-dependant changes are responsible for increases in soil cation-exchange capacity (CEC). The current study established that CEC differed from habitat to habitat, and changed from one soil depth to another. CEC was generally higher in deeper soil than in surface soil; it was also higher in forest soils than in orchard and farmland soils (Fig. 4b). This can be explained as due to differences in ion strength that affect effective charge. It suggests that the local reforestation program is helping increase the CEC storage capacity of the area.

In order to better understand the effect of pH and CEC on C, N and P stoichiometry, we used linear regression analysis (Fig. 5). The results of the analysis show that the average pH for each plant community was positively correlated with C, N and P content ($r^2 = 0.65$, 0.48 and 0.32, respectively, $p < 0.01$). Conversely, pH was negatively correlated with C:N, C:P, and N:P ratios ($r^2 = 0.55$, 0.24 and 0.14, respectively, $p < 0.01$) (Fig. 5b). When soil pH is in the 6–7 range, soil P availability is greatest (for most soils) (Nyakatawa et al., 2012). The pH for the soil samples collected during this study (from all habitats) generally ranged below 6, so the correlation between pH and P content, or pH and C:N and C:P ratios, was low. The CEC showed a similar lack of correlation with the C, N and P stoichiometry. The regression coefficient is lower for CEC than for pH; r^2 coefficients generally ranged below 0.25. It is possible that most of the nutrient cations associated with CEC may have come from plant decomposition or fertilizer use, predominantly in surface soils; however, soil chemistry is complicated and there are certainly other factors that would have affected these results.

4.5. Limits on C sequestration

Forests possess the maximum C pool potential for terrestrial ecosystems and play a prominent role in global terrestrial C cycling (Pan et al., 2012). As Fig. 6a and b shows, in comparison to changes in C density and storage between 1984 and 2012, C density and storage in all forest land use types investigated exhibited a sharp increase between 1984 and 2002, based on data from Wang et al. (2004) and Li and Yuan (2001). However, mixed and masson pine forests exhibited a decrease in total C storage over the past decade, which can easily be explained by the reforestation projects implemented, where forested area sharply increased between 1984 and 2002. Why mixed and masson pine forests decreased in their C storage capacity may be due to the fact that soil is not an unlimited C sink. A C saturation threshold exists beyond which C storage cannot increase (Marland et al., 2001; Gao et al., 2011; Ma et al., 2013).

In the study area, fir, slash pine, and masson pine forests were widely planted in the 1980s as part of the National Conversion of Cropland to Forest Reforestation Program. These species start bearing seeds after 15–40 years and can be harvested after 20–25 years. Since they are fast-growing species, the plantations planted in the 1980s are today close to maturity. Hence, their C sequestration capacity would naturally have declined. Gulde et al. (2008) and Chung et al. (2010) reported that higher amounts of C inputs did not further increase SOC stocks for soils that were part of long-term experiments. The cause of this apparent anomaly becomes clear after discerning that C saturation was reached either in the soil or the terrestrial ecosystem surrounding it (Stewart et al., 2007; Heitkamp et al., 2012). This threshold appears to be influenced by many factors, such as climate, plant type, soil texture and temperature, microbial activity, mineral content, available moisture, human activity, and the past history of SOC inputs and physical disturbances (Post and Kwon, 2000; Scholes and Noble, 2001; Russell et al., 2007).

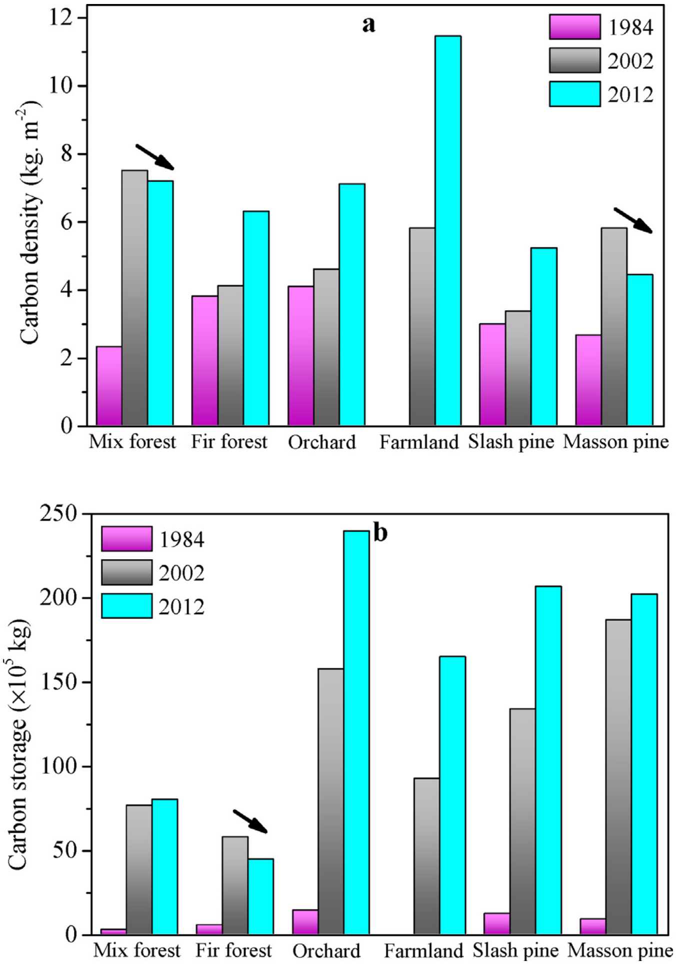

Fig. 6. Changes in C density and storage under different land use types between 1984 and 2012 in QFES.

5. Conclusions

In this study, we found that the species differed in traits could influence on C, N and P dynamics and its stoichiometry, and species with different root traits that resulted in different vertical and horizontal distributions of C, N and P, reflecting differences in nutrient uptake by plants and microbial dynamics drove the biggest changes in soil C, N and P. In south China, P is important limited factor and C, N and P stoichiometry is particularly influenced by P limitation in red soil area. The differences among species in soil properties are related to C, N, and P content and stoichiometry, and soil acidification and low pH in this area maybe is important factor driving the change of C, N and P dynamics and storage. Land use change and time noticeably effected soil C and N content. C, N, and P content in soil changed with soil depth under different land use types. The C:N ratio for surface soil in the study area grew over time, and C:P and N:P ratios for both 2002 and 2012 were lower in samples taken from orchard and farmland soils than those taken from forest soil samples. P is the crucial limiting factor on soil fertility in southern China. Additionally, C, N, and P stoichiometry is particularly influenced by P limitation in the red soil typical of the region.

The conclusion is that forests cannot store unlimited amounts of C. Thresholds exist. One important factor of this limitation is maturity. When young forests mature, their capacity for C, N, and P storage decline. Therefore, assessing impacts of reforestation and cultivation on SOC will require long-term experiments to understand the effects of inherent spatial variability in SOC densities under different land use types. Management agencies aiming to maintain or increase SOC stocks on forestry and agricultural land should pay close attention to the effects of management practices in these areas. Improved soil management and land use practices should enhance soil fertility through nutrient recycling and C storage as well as sequestering some of the excess C that is driving global climate change.

Acknowledgements

We thank Brian Doonan (McGill University, Canada) for his help in revising this paper and giving useful suggestion. This paper was financially supported by the National Nature Science Foundation of China (nos. 31290223 and 31200404) and the Program for "Bingwei" Excellent Talents from the Institute of Geographic Sciences and Natural Resources Research, CAS. The authors would also like to thank their anonymous reviewers for their helpful remarks.

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