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2015 INTERNATIONAL SYMPOSIUM ON FOREST SOILS

Soil pH, organic matter, and nutrient content change with the continuous cropping of *Cunninghamia lanceolata* plantations in South China

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Abstract

Purpose Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an important native tree species in China. Consecutive cropping traditionally occurs in Chinese fir plantations (CFPs), but this practice has resulted in productivity declines in subsequent rotations. This study was designed to better understand the change of soil properties in the continuous cropping CFPs.

Materials and methods We investigated soil pH, soil organic matter (SOM), and nutrient contents in different soil layers and in rhizosphere soil (RS) and non-rhizosphere soil (NRS) under CFPs of different ages and in different rotations.

Results and discussion In the upper (0–20 cm) soil layer, soil pH decreased, while SOM increased, beneath mature CFPs with consecutive rotations. Total nitrogen (TN), available potassium, and available phosphorus contents in the upper soil layers did not differ significantly with consecutive rotations. Soil pH in RS was significantly lower than in NRS under mature plantations of the third rotation. Soil organic matter, TN, and available nitrogen did not differ between RS and NRS. Available phosphorus in RS was consistently lower than in NRS, and was highly deficient in the third rotation.

Conclusions We conclude that no severe soil nutrient degradation occurred in the continuous cropping CFPs examined in this study, with soil acidification and phosphorus deficiency being two primary problems observed.

Keywords Chinese fir plantations · Continuous cropping · Nutrients · Organic matter · pH · Rhizosphere

1 Introduction

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an indigenous tree species in South China. Due to desirable features such as fast growth, pest and disease-resistance, and good timber quality, it is historically one of the most important timber tree species in South China and has been widely planted for decades in hilly and mountainous tropics and subtropics of China. Many natural forests have been converted into monocultural Chinese fir plantations (CFPs) in South China since the middle of the twentieth century (Xu et al. 2005). Plantations of this species cover more than 1.10×10^7 hm^{-2}, accounting for over 6.66 % of the total forest area in China (State Forestry Administration of the People's Republic of China 2014).

Consecutive rotation of Chinese fir is a traditional silvicultural practice and has been widely practiced in South China (Yang et al. 2005). A new rotation is usually established after clear-cutting, slash burning, and tillage prior to planting. In recent decades, researchers have found that CFPs in the continuous rotation system exhibited reduced growth rates and yields (Fang et al. 2010). For example, the heights of dominant Chinese fir trees of the second and third rotations decreased by 7 and 23 % relative to the first rotation, respectively (Bi et al. 2007). Additionally, the standing wood volumes of the second and third rotations of CFPs were 30 and 47 %

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lower than the first rotation, respectively (Bi et al. 2007). Plantation biomass growth rates decreased by 24 % from the first to the second rotation and by 40 % from the second to the third rotation (Zhang et al. 2004). The decline of productivity in continuously cropped Chinese fir ecosystems remains an outstanding problem in plantation management in South China (Yang et al. 2005). Degradation of successively planted forestland of other tree species has caused concerns since the nineteenth century, and extensive studies on mechanisms and countermeasures have been conducted in other parts of the world (Raynaud 2010). Results, however, are by no means consistent. The total volume yield in a second-generation Norway spruce (*Picea abies* (L.) Karst.) stand was 40 % higher than that of the first generation and dominant tree height at a stand age of 40 years was about 20 % greater in the second generation than in the first (Eriksson and Johansson 1993).

Since the 1980s, continuous cropping of Chinese fir has been reported to cause soil degradation with regard to physiochemical, biological, and biochemical properties (Chen and Wang 2003; Sun et al. 2003; Bi et al. 2007; Zhao et al. 2013). For example, under continuous rotations, water holding capacity and permeability of the surface soil declined and bulk density increased (Yao and Xie 1991); additionally, soil pH decreased and available P and N declined sharply. Soil organic matter (SOM) contents in the second rotation decreased by 10 % relative to the first rotation, and further decreased by 15 % in the third rotation relative to the second rotation (Huang et al. 2004). Soil enzyme activity in the second rotation was significantly lower than that of the first (Chen and Wang 2003), and microbial community diversity, as well as microbial biomass, decreased with successive rotations (Liu et al. 2010). The above aspects of soil degradation were believed to result from successive cropping, short rotations (around 25 years), whole-tree harvest, and tillage (Zhang et al. 2004; Liu et al. 2010). For example, Yang et al. (2005) reported that N removal via clear-cutting from CFPs was 233 kg hm^{-2} and, compared to pre-burning, topsoil organic C and total nitrogen (TN) contents were reduced by 17 and 19 %, respectively, just two days after slash burning. Also, timber harvest caused substantial loss and redistribution of SOM and N (Wear and Greis 2002), and exerted negative effects the ecosystem C balance (Chen et al. 2013).

Some scientists, however, have reported that soil degradation does not necessarily develop consistently with continuous cropping. Wei et al. (2012) showed that soils under CFPs of the third rotation had higher SOM, total P and K, and available nitrogen contents than those of the second rotation, hypothesizing that sustainable management of CFPs could be attained in the continuous cropping system if plantation density was optimized. Also, soil fertility changed but did not necessarily decrease with plantation development. Sun et al. (2003) observed that comprehensive soil fertility improved

under mature plantations relative to the half-mature plantations in the first rotation. According to Wang et al. (2010), contents of SOM, TN, available N, and available K decreased in half-mature plantations, but significantly increased in mature plantations and reached maximum levels in overly mature plantations. Ma et al. (2007) also noticed that SOM contents increased with CFPs growth. Wu et al. (2011) compared soil fertility under CFPs of different ages and found that fertility was highest in overly mature forests and decreased through mature forests, near-mature forests, and young forests to its lowest level in half-mature forests. Zhou et al. (2016) also found that young stands of CFPs depleted soil nutrients and showed low nutrient return, while mature or over-mature stands had greater nutrient return leading to better recovered nutrient pools in forest soil.

Consequently, it remains uncertain whether soil degradation is a universal problem for CFPs managed under continuous rotations, and the manner in which pH, SOM, and nutrient contents change in response to stand age and rotation in CFPs. Additionally, the severity of soil degradation associated with continuous rotation requires more careful and detailed examination. For this purpose, we investigated soil pH, SOM, and nutrient contents under different-aged CFPs in the first, second, and third rotations and compared soil pH, SOM content, and macronutrient availability in the rhizosphere soil (RS) with those of the non-rhizosphere soil (NRS).

2 Materials and methods

2.1 Study area and site description

The study area was located in Xidong Forest Farm, Jian'ou City (27° 03′ N, 118° 20′ E), Fujian Province, one of the central production regions of CFPs in China. According to the space-for-time ecological sequential comparison method (Fukami and Wardle 2005), CFPs in the first rotation, second rotation, and third rotation (1, 2, and 3, respectively) that were either young (y; 5–6 years old), half-mature (h; 12–15 years old), and mature (m; 25–30 years old) were carefully selected for the study, with each rotation and age combination (1-y, 1-h, 1-m, 2-y, 2-h, 2-m, 3-y, 3-h, and 3-m) being represented by a typical plantation. The selected plantations were in close proximity, shared the same soil type, occurred at similar elevation (530–560 m) and exhibited comparable micro-topography (Table 1). The soil was developed from granite parent material and classified as dark red soil in the Chinese soil classification system. Soil depths under the selected plantations were mostly greater than 1 m, with slopes between 20 and 30 °. The study area belonged to the middle subtropical monsoon climatic zone, with a mean annual temperature of 18.7 °C and a mean annual precipitation of 1670 mm, which mainly occurred from March to August. The topsoil bulk

Table 1 Basic information of plantation stands

Plantation	Age (year)	Slope (°)	Aspect	Stem density (stem hm^{-2})	Height (m)	DBH (cm)	Stock volume (m^3 hm^{-2})
1-y	6	28	West	3150	6.30	9.35	78.75
1-h	11	27	Northwest	2760	11.78	14.50	287.32
1-m	31	30	Southeast	1200	18.80	24.40	529.32
2-y	7	28	East	3090	5.66	8.40	56.86
2-h	12	27	Northwest	2950	10.30	13.09	221.68
2-m	31	20	West	1650	15.10	19.95	477.24
3-y	6	30	South	3050	7.40	5.40	43.16
3-h	12	27	Northwest	2625	9.90	10.60	126.0
3-m	31	28	North	1620	17.20	19.80	437.24

1-y, 1-h, 1-m young, half-mature, and mature Chinese fir plantation in the first rotation, respectively; 2-y, 2-h, 2-m young, half-mature, and mature Chinese fir plantation in the second rotation, respectively; 3-y, 3-h, 3-m young, half-mature, and mature Chinese fir plantation in the third rotation, respectively

density was 1.20 ± 0.03 g cm^{-3}, capillary porosity was 44.8 ± 1.3 %, and field capacity was 421.0 ± 27.9 g kg^{-1}. Before plantation establishment, clear-cutting, slash piling and burning, and complete site tillage were carried out. Immediately after plantation establishment, calcium superphosphate was applied at 100 g tree^{-1} into a 5-cm deep tunnel circling the tree; no fertilization was conducted before harvesting.

2.2 Soil sampling

In each selected plantation, three plots (each 20 m × 20 m) were established for soil sampling. Within each plot, five soil profile pits were dug on an S-shaped route across the plot. Soil samples of 1 kg were collected from the 0–20, 20–40, and 40–60-cm layers of each profile, respectively. Soils collected from the same layer of the five profiles were mixed evenly and a composite soil sample was extracted using the quartering method (dividing the soil into quarters and collecting from the two quarters facing opposite one another), which was regarded as representative of the given soil layer of the plot.

Additionally, in each plot, a composite soil sample was collected from the 0–40-cm layer of the above-mentioned pits, which was designated as the non-rhizosphere soil (NRS) sample. When collecting NRS soil, only soils > 3 cm from visible roots was collected. Five dominant trees in each plot were selected randomly from which to collect rhizosphere soil (RS). Under each tree, full-length roots with diameter ≤ 2 mm in the 0–40-cm soil layer in the pits were randomly chosen and 200 g soil within 1 cm of the root surface was collected. Soil sampled from the roots of the five trees was mixed to constitute a composite RS sample for the plot.

2.3 Determination of soil properties

The chemical properties of soil were analyzed according to Carter and Gregorich (2008). Soil pH was measured in deionized water (1:2.5 *w/v*) using a glass-calomel combination electrode. Soil organic carbon (SOC) was first measured by wet oxidation, and then was calculated as soil organic matter (SOM) using the transfer factor 1.724. Both total nitrogen and available nitrogen were measured with the modified Kjeldahl method. Extraction of total and available phosphorus was accomplished by digestion with H_2SO_4–$HClO_4$ and extraction with HCl–H_2SO_4, respectively, and then measured using the molybdenum-blue method. Total and available potassium were determined by digestion with HF and extraction with NH_4OAc, respectively, and flame photometry.

2.4 Statistical analyses

All data were analyzed using SAS. One-way analysis of variance (ANOVA) was conducted to determine the changes in soil pH, SOM and nutrient contents. If significant effects were detected ($\alpha = 0.05$), Duncan's multiple range test (DMRT) procedure was used to separate the mean values of each plantation.

3 Results

3.1 Soil pH and SOM under CFPs of different ages and rotations

Fluctuations of soil pH among plantations of different rotations and ages were observed in every soil layer. Soil pH values in the 0–20 and 20–40-cm soil layers under the 3-m plantation were significantly lower than their respective counterparts under the 1-m plantation (Fig. 1). However, significant increases in soil pH were observed in the 20–40 and 40–60-cm layers at the transition from 1-m to 2-y plantations. For 0–20-cm layers, no significant change in soil pH were observed at the transition from 1-m to 2-y, or from 2-m to 3-y, indicating that pH did not decrease consistently with the transition of rotation in CFPs.
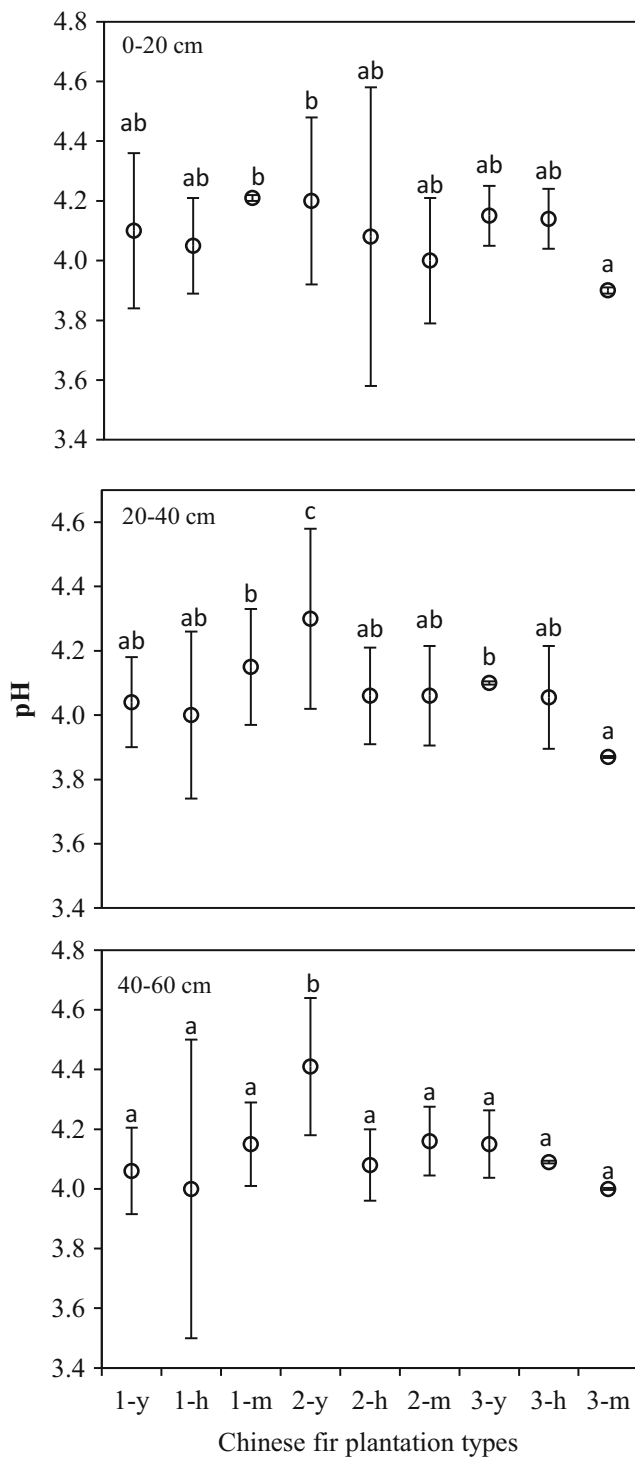
Fig. 1 Mean soil pH (±SE) under different Chinese fir plantations. Bars marked with different letters within the same pane are significantly different (Duncan's test, $\alpha = 0.05$)

Fig. 2 Mean soil organic matter contents (±SE) under different Chinese fir plantations. Bars marked with different letters within the same pane are significantly different (Duncan's test, $\alpha = 0.05$)

SOM content in the surface soil generally increased with CFPs ages and rotations (Fig. 2), with SOM content in the 0–20-cm layer under the 3-m plantation increasing 200 % over that of the 1-y plantation. SOM content increases were less dramatic and consistent in the 20–40 and 40–60-cm layers,
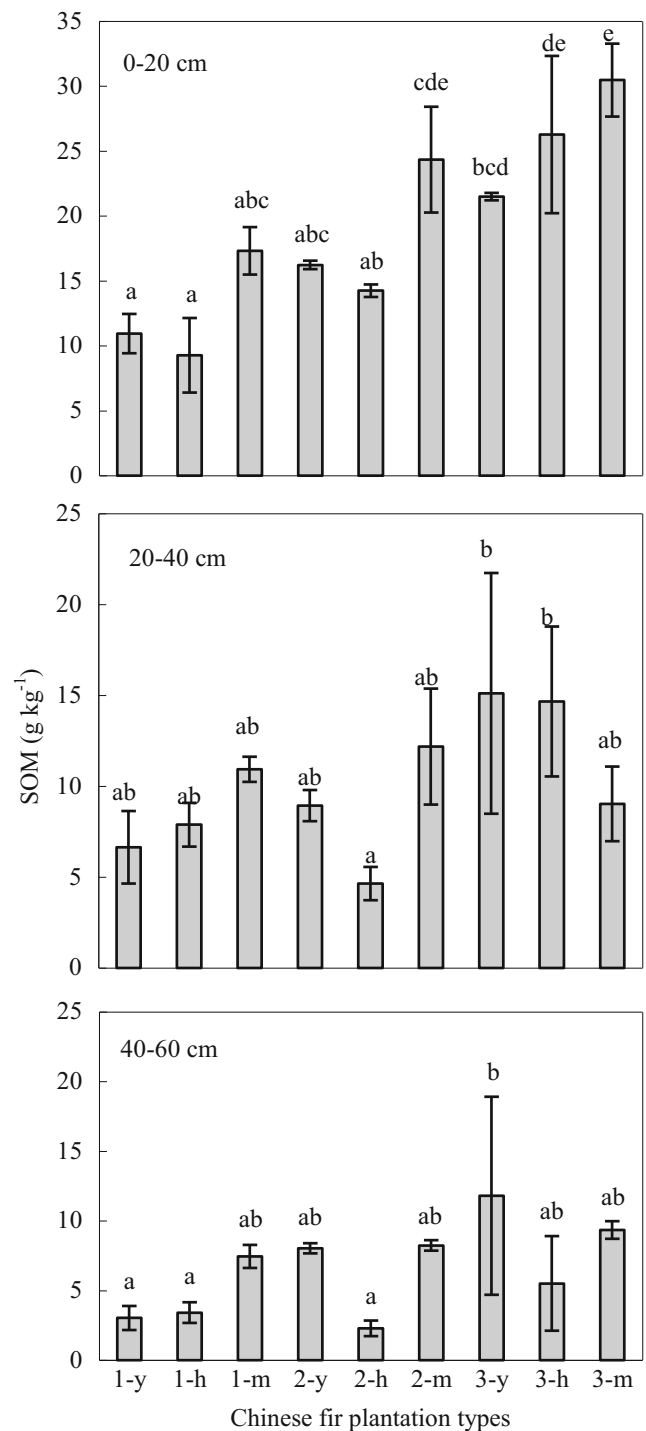
with SOM contents of the 3-y and 3-h plantations being significantly greater than that of the 2-h plantation in the 20–40-cm layer, and SOM contents of the 3-y plantation being significantly greater than those of the 1-y, 1-h, and 2-h plantations in the 40–60-cm layer.

3.2 Soil nutrient contents under CFPs of different ages and rotations

Soil TN and available N fluctuated with rotation and age (Figs. 3 and 4, respectively). Available N in the surface soil was lowest under 1-y plantations and highest under 2-m plantations, and this was consistent at other soil depths (Fig. 3). Available N in all soil layers increased with CFPs growth in the first rotation, reached a plateau under 2-m plantations, and then dropped and remained somewhat stable in the third rotation (Fig. 3).

Available P was extremely low in each of the three soil layers, with contents below 5, 4, and 2 mg kg^{-1} for the 0–20, 20–40, and 40–60-cm layers, respectively (data not shown). Available K content in the surface soil was lowest in the 2-m plantations and highest in the 2-h plantations, but overall available K content did not show any obvious pattern in response to plantation age or rotation (data not shown).

3.3 Rhizosphere soil pH, SOM, and nutrients

In our study, mean pH values of the RS were lower than those of the NRS for all plantations; however, only the difference in pH values between RS and NRS in the 3-m plantation was statistically significant. The pH values in RS in 1-m plantations declined from 3.95 to 3.75 in 2-m plantations and further to 3.60 in 3-m plantations, exhibiting notable acidification in RS. Within the second and third rotations, pH in RS dropped sharply with plantation growth (Table 2).

In plantations of the first and second rotations, SOM in RS was higher than that in NRS; in the 3-y plantations, SOM was similar in RS and NRS; in 3-h and 3-m plantations, however, SOM was lower in RS than in NRS (Table 2). In addition, a decrease in SOM in both RS and NRS occurred at the transition from 1-m to 2-y and 2-m to 3-y.

Contents of TN, available N, and available K in RS showed little difference from those of NRS and no differences were significant under any plantation except available K under 3-h (Tables 2 and 3). Mean available P contents, however, were always lower in RS than in NRS, with significant differences occurring under 1-m, 2-m, 3-y, 3-h, and 3-m plantations (Table 3). In this study, it appears that P depletion in the rhizosphere became severe under third-rotation plantations.

4 Discussion

Soil pH is one of the most important soil chemical indices, influencing plant nutrient availability and many other soil properties. Yang et al. (2001) reported that surface soil pH in the first-rotation CFPs dropped from 5.02 to 4.90 in third-rotation stands, while our results revealed a drop from 4.20 to 3.90 over the same period, confirming the previously
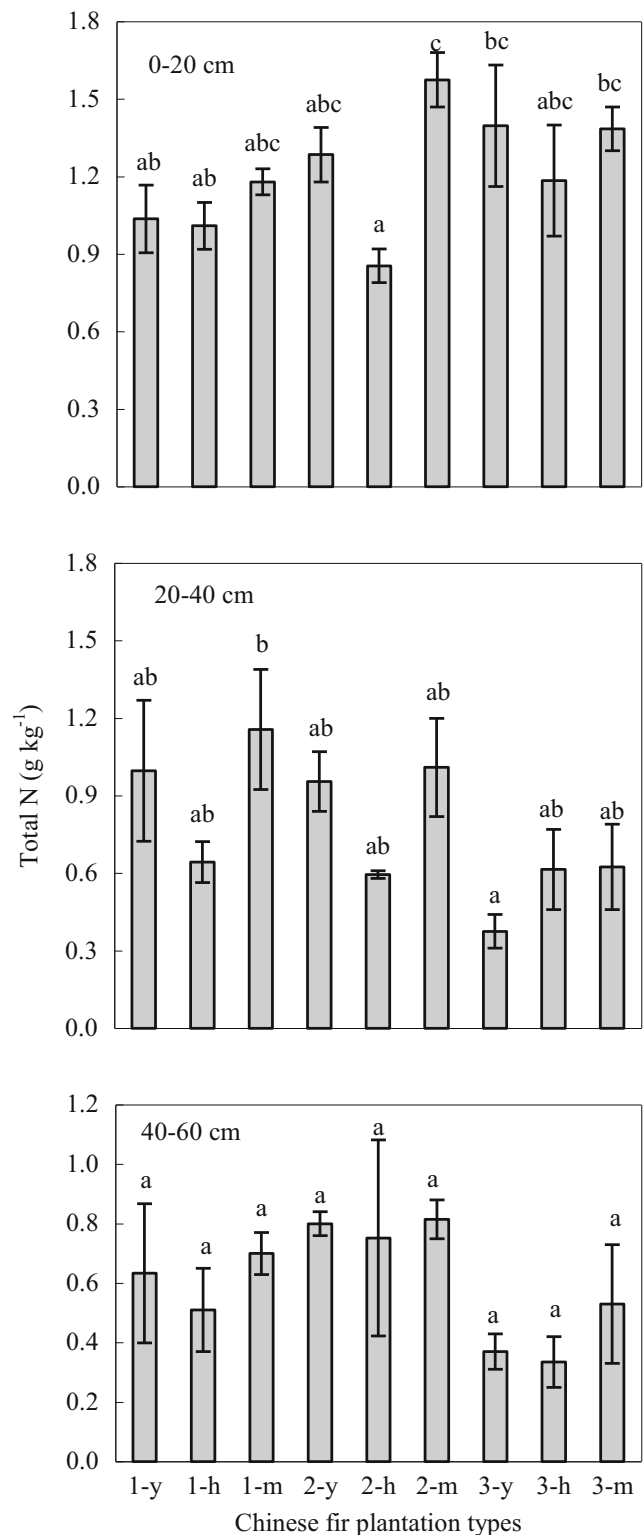

Fig. 3 Mean total nitrogen contents (±SE) under different Chinese fir plantations. Bars marked with different letters within the same pane are significantly different (Duncan's test, $\alpha = 0.05$)

described acidification trend. However, we observed pronounced pH increases in the 20–40 and 40–60-cm layers at the transition from 1-m to 2-y plantations, which might be a
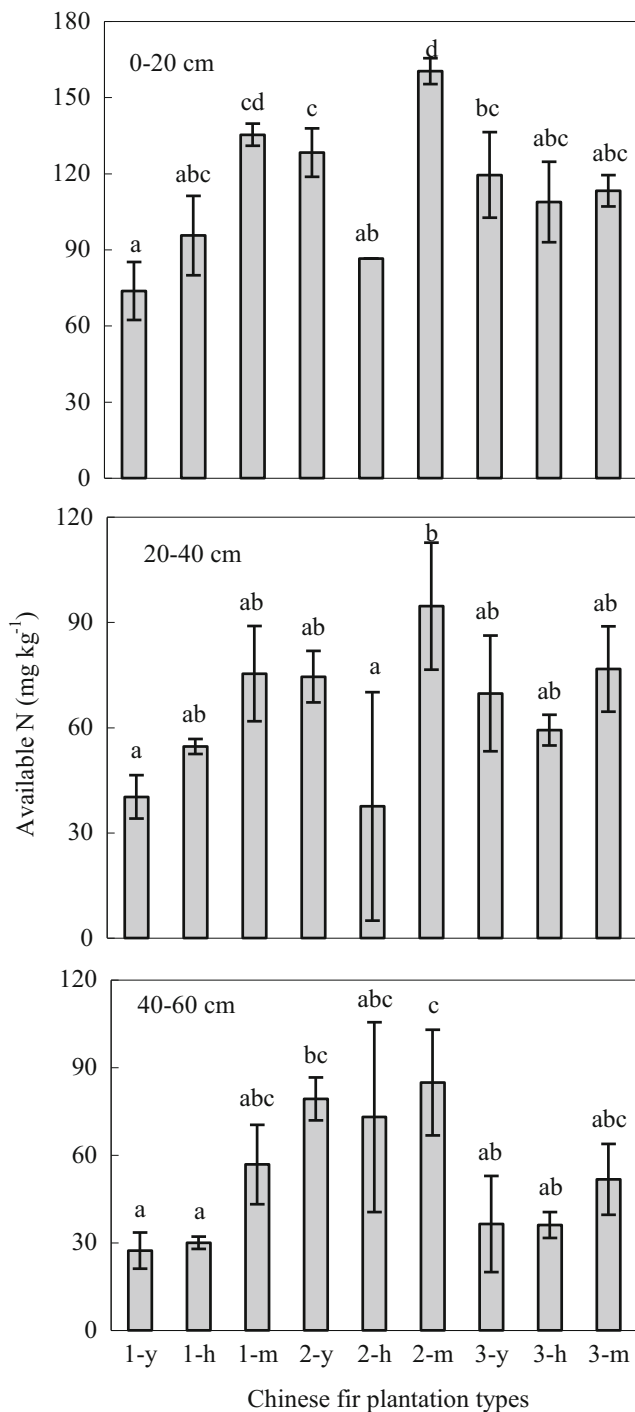
Fig. 4 Mean available nitrogen contents (±SE) under different Chinese fir plantations. Bars marked with different letters within the same pane are significantly different (Duncan's test, $\alpha = 0.05$)

result of fertilization and/or slash burning between rotations (Chen 1998). Burning has been shown to accelerate decomposition of organic acids in soil and to return basic ions to the soil, thereby increasing pH (Tanaka et al. 2005). Subsequent decreases in soil pH likely resulted from base ions being taken up by trees while organic acid root exudations gradually reaccumulated in the rhizosphere.

SOM serves as a storage reservoir for soil nutrients and has important effects on almost all soil chemical, physical, and biological properties (Tanaka et al. 2005); consequently, SOM is generally accepted as an important criterion for assessment of sustainable forest management (Haynes and Beare 1996). Chen et al. (2013) showed that soil organic C (SOC) pools in CFPs increased only between 16 to 21 years, and then stabilized until reaching an over-mature stage. Moreover, increasing rotation length could cause a decrease in SOC (Skjemstad et al. 2008). Our results showed that SOM in the surface soil generally increased with age of CFPs. Further, although non-significant, 2-y and 3-y plantations exhibited a decrease in mean SOM of surface soil (0–20 cm) relative to 1-m and 2-m plantations, respectively, suggesting that SOM in the surface soil declines after harvesting. In accordance with previous studies, we conclude that SOM in CFPs in our study exhibited changes because (1) the increase of both litterfall and fine-root biomass of Chinese fir trees can cause a high accumulation of SOM from young to mature stage in the same rotation (Skjemstad et al. 2008; Chen et al. 2013); however, (2) intensive management practice in forest harvesting, such as clear-cutting, burning and/or removal of harvest residue and forest litter have led to a dramatic decrease in SOM after harvesting or in the young stage of next rotation (Yang et al. 2005; Guo et al. 2016).

Surface soil TN remained relatively stable, with minor fluctuations throughout the experiment. This result was inconsistent with that of Luo and Zhang (2007), who found that nitrogen content in soils under second-rotation CFPs were 8.6 % lower than those of the first rotation, while those under the third rotation were 23.0 % lower than the second. Wang et al. (2010) attributed such decreasing soil nitrogen contents to relatively low nitrogen return through litterfall over the course of consecutive rotations.

The rhizosphere is recognized as one of the most important compartments of terrestrial ecosystems due to its major effect on biogeochemical cycles (Raynaud 2010). Rhizosphere soil has been found to be quite different in chemical properties and nutrient availability from NRS due to root absorption and rhizodeposition activities (Bi et al. 2007). In our study, pH values in the RS were lower than those in the NRS under all plantations (Table 3), although this was only significant in 3-m plantations. This pH difference may be partly because Chinese fir absorbed more nutrient bases such as K^+, Ca^{2+}, and Mg^{2+} and fewer anions from the soil, which consequently resulted in base reduction in the root-soil interface (Hu et al. 2006), and therefore a decrease in pH. Additionally, root-exuded organic acids, CO_2, and HCO_3^-, as well as secretions by microorganisms in the rhizosphere, have also been shown to contribute to the acidification of the RS (Ingestad 1987). The pH reduction in RS confirmed to some extent the widely reported soil acidification in continuous cropping of CFPs (Ingestad 1987; Guo et al. 2016).

Table 2 Mean soil pH, organic matter, and total N in rhizosphere (RS) and non-rhizosphere soils (NRS) under Chinese fir plantations of different rotations and ages

Plantations	pH		Organic matter (g kg^{-1})		Total N (g kg^{-1})	
	RS	NRS	RS	NRS	RS	NRS
1-y	3.85 ± 0.05bc	4.05 ± 0.05ab	15.26 ± 0.34a	9.77 ± 1.63a	0.93 ± 0.05a	0.95 ± 0.17a
1-h	3.95 ± 0.05 cd	4.05 ± 0.05ab	18.79 ± 0.05a	13.40 ± 1.03ab	1.18 ± 0.22ab	0.95 ± 0.13a
1-m	3.95 ± 0.05 cd	4.2 ± 0.050b	25.72 ± 4.15ab	17.22 ± 3.15abc	1.19 ± 0.20ab	1.21 ± 0.07ab
2-y	4.05 ± 0.05d	4.20 ± 0.10b	22.45 ± 1.96a	16.52 ± 0.33abc	1.24 ± 0.05b	1.28 ± 0.10ab
2-h	3.80 ± 0.00bc	4.10 ± 0.20ab	18.08 ± 0.56a	9.72 ± 0.47a	0.93 ± 0.01a	0.86 ± 0.06a
2-m	3.75 ± 0.05ab	4.00 ± 0.10ab	42.05 ± 14.42b	24.35 ± 4.06bcd	1.36 ± 0.13b	1.57 ± 0.11b
3-y	4.05 ± 0.05d	4.15 ± 0.05ab	21.98 ± 0.77a	21.50 ± 0.29bcd	0.97 ± 0.14a	1.40 ± 0.34ab
3-h	3.80 ± 0.10bc	4.15 ± 0.05ab	22.41 ± 4.12a	26.27 ± 6.07 cd	1.17 ± 0.17ab	1.19 ± 0.21ab
3-m	3.60 ± 0.02a	3.90 ± 0.01a	25.51 ± 0.13ab	30.79 ± 2.80d	0.96 ± 0.01a	1.38 ± 0.09ab

Data followed by different lowercase letters in the same column are significantly different (Duncan's test, $\alpha = 0.05$)

1-y, 1-h, 1-m young, half-mature, and mature Chinese fir plantation in the first rotation, respectively; *2-y, 2-h, 2-m* young, half-mature, and mature Chinese fir plantation in the second rotation, respectively; *3-y, 3-h, 3-m* young, half-mature, and mature Chinese fir plantation in the third rotation, respectively

Nutrient deficiency, particularly that of P, has been commonly regarded as an important factor leading to yield decline of CFPs (Chen 2003; Bi et al. 2007). Of all the nutrients studied, P was identified as most likely to be an important limiting factor to CFPs in the third rotation. In the third rotation, available P decreased (especially for RS) compared with the first and the second rotation (Table 3). Moreover, mean available P content was always lower in RS than in NRS, with the differences under 1-m, 2-m, 3-y, 3-h, and 3-m plantations being significant (Table 3). Over 80 % of total P in CFP ecosystems is organic P, which has a large effect on P availability (Chen 2003). Organic P must be hydrolyzed to available P by phosphatases, however, and this does not meet requirements for Chinese fir tree growth (Chen 2003). P fertilizer, such as calcium superphosphate, is therefore applied routinely. Unfortunately, when phosphate is applied as fertilizer in soils, it is rapidly immobilized owing to fixation by bonding with calcium, magnesium, aluminum, and iron (López-Arredondo et al. 2014). The production and root exudation of organic acids is believed to be an important factor in enhancing P availability in soils highly prone to P fixation (López-Arredondo et al. 2014). For example, Yu et al.

Table 3 Mean soil available N, available P, and available K in rhizosphere and non-rhizosphere soils under Chinese fir plantations of different rotations and ages

Plantations	Available N (mg kg^{-1})		Available P (mg kg^{-1})		Available K (mg kg^{-1})	
	RS	NRS	RS	NRS	RS	NRS
1-y	77.96 ± 19.20ab	74.12 ± 19.75a	3.63 ± 0.13c	4.28 ± 0.48 cd	93.26 ± 12.47ab	89.95 ± 6.80a
1-h	48.62 ± 1.83a	94.60 ± 27.06ab	4.80 ± 0.02d	5.50 ± 0.28d	86.66 ± 13.52ab	104.39 ± 6.73ab
1-m	171.04 ± 23.77c	134.10 ± 7.31bc	2.01 ± 0.24b	4.13 ± 0.37bc	71.91 ± 1.77ab	72.23 ± 21.07a
2-y	123.49 ± 32.29bc	128.25 ± 9.51bc	1.65 ± 0.60b	2.38 ± 0.13a	57.41 ± 22.37a	68.35 ± 4.75a
2-h	78.51 ± 4.39ab	84.05 ± 5.12ab	4.49 ± 0.26d	5.22 ± 0.26 cd	107.55 ± 15.30b	121.63 ± 5.76b
2-m	105.57 ± 13.17ab	166.28 ± 2.50c	1.33 ± 0.29b	2.87 ± 0.37a	63.44 ± 14.81ab	190.20 ± 28.17b
3-y	88.38 ± 0.37ab	119.47 ± 16.82ab	0.50 ± 0.08a	3.00 ± 0.23ab	74.00 ± 4.21ab	68.15 ± 6.78a
3-h	116.54 ± 27.06bc	108.79 ± 15.80ab	0.20 ± 0.05a	4.47 ± 0.50 cd	85.77 ± 0.26ab	77.16 ± 0.88a
3-m	96.52 ± 12.34ab	113.25 ± 6.22ab	0.90 ± 0.06a	2.74 ± 0.50a	76.93 ± 14.35ab	72.44 ± 2.66a

Data followed by different lowercase letters in the same column are significantly different (Duncan's test, $\alpha = 0.05$)

1-y, 1-h, 1-m young, half-mature, and mature Chinese fir plantation in the first rotation, respectively; *2-y, 2-h, 2-m* young, half-mature, and mature Chinese fir plantation in the second rotation, respectively; *3-y, 3-h, 3-m* young, half-mature, and mature Chinese fir plantation in the third rotation, respectively

(2008) reported that organic acid exudation from the roots of Chinese fir increased under stress from low P. Data from Zhao (2012) showed that compared with the first generation CFPs, the content of organic P, Al-P, and Ca-P increased, while the soil P activation coefficient decreased in second-generation CFPs. Moreover, Liao et al. (2001) found that some root exudations, especially HPO_4^{2-}, significantly decreased in the second-generation CFPs. This suggests that low availability of P in the third rotation was principally due to the fact that P is prone to chemical or organic fixation, while both root exudations and microbial activity in soil decreased with succession of CFPs. The extent to which these limitations in P supply during latter rotations of CFPs may be overcome by fertilization and other means should be the target of further research.

In this study, although some nutrients showed a decreasing trend in the consecutive rotation system, no statistically significant decrease in any nutrient content in any of the soil layers was observed under 3-m plantations relative to the beginning of the first rotation. This implies that there may be other factors contributing to the observed yield decline of CFPs. For example, autotoxicity was reported to be a major problem for continuous cropping ecosystems and a drawback for Chinese fir growth (Fernandez et al. 2008). Some cyclic dipeptides have been shown to be highly active allelochemicals and found to be highly concentrated in soils of second-rotation CFPs, where they proved to be phytotoxic to Chinese fir (Kong et al. 2008).

Numerous measures have been investigated as a means to help prevent soil degradation and yield decline in consecutively cropped CFPs systems. Intercropping was conducted in young CFPs and proved a good silvicultural practice for ameliorating nutrient depletion (Wang et al. 2005). Additionally, mixed plantation practices have been recommended for Chinese fir planting by many scientists to maintain soil fertility (Luan et al. 2010). Furthermore, it has been proposed that slash burning and overall tillage should be abandoned and replaced with no-tillage site preparation and herbicide application (Burger 2009). Reasonable and efficient fertilization systems should be identified and alternative cropping methods, other than continuous cropping systems, established in regions where soil degradation has resulted from consecutive rotation practices.

One shortcoming of this study is the lack of stand replicates, associated with the logistical challenge of identifying multiple stands across the landscape. As soil characteristics are highly heterogeneous, especially in hilly regions in south China, the lack of stand replicates might compromise the reliability of our conclusions in examining the effects of continuous cropping on soil fertility. In spite of these limitations, however, this study still provides useful insight into effects of forest management in tree plantations on soil properties.

5 Conclusions

Soil pH in the 0–20 and 20–40-cm layers beneath mature CFPs decreased with consecutive rotations; however, soil pH did not decrease consistently with the transition of CFPs rotation, potentially as a result of anthropogenic activities, such as slash burning and fertilization between rotations. Accumulation of SOM in the surface soil was observed under continuously cropped CFPs, with SOM content under 3-m plantations being two times higher than that under 1-y plantations. TN, available N, and available K did not show any obvious patterns with age and rotation. TN, available N, and available K contents in RS showed little difference from those in NRS; however, pH and available P in RS were consistently lower than in NRS and tended to decrease with continuous cropping. Generally, soil degradation in the continuous cropping system of our study appeared less serious than expected based upon previous reports. Soil acidification and available P deficiency appear to be two of the major potential problems resulting from Chinese fir continuous rotation practices.

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