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# SOIL NUTRIENTS DYNAMICS IN BROADLEAVED FOREST AND CHINESE FIR PLANTATIONS IN SUBTROPICAL FORESTS

**Selvalakshmi S[1, 2], Vasu D[3], Zhijun H[1], Guo F[1, 2] & Ma XQ[1, 2, *]**

[1]*College of Forestry, Fujian Agriculture and Forestry University, Shangxiadian Road, Cangshan District, Fuzhou, 350002, China*
[2]*Chinese Fir Engineering Technology Research Center of the State Forestry Administration, Fuzhou 350002, People's Republic of China*
[3]*ICAR-National Bureau of Soil Survey and Land Use Planning, Nagpur, Maharashtra- 440 033, India*

**lxymxq@126.com*

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This study explored how soil nutrients are affected by the monoculture Chinese fir (*Cunninghamia lanceolata*) plantation and natural broadleaved forest. A total of 11 different age classes of Chinese fir at four rotations were investigated. Five quadrats were selected in each age class in which three pits were dug in each quadrat at five depth intervals. In each sample plot, a total of 75 samples were collected. Composite soil samples were analysed for total and available nitrogen (N), phosphorus (P) and potassium (K). Results showed that amount of soil nutrients was significantly lower in Chinese fir plantations than in natural broadleaved forests. Soil depth and age of plantations significantly influenced soil nutrients. Further, total N, P, K, $NH_4^+$-N, available P and available K decreased as the number of rotations increased. Successive cultivation of Chinese fir plantation led to decline in the amounts of soil nutrients in the plantations compared with those of natural broadleaved forest stands.

Keywords: Southern China, *Cunninghamia lanceolata*, intercropping, successive cultivation, soil nutrients

## INTRODUCTION

The increasing demand for forest products has led to an increase in planted forest area worldwide. Global forest plantations are estimated to cover an area of 291 million ha, corresponding to 7.2% of total forested area (FAO 2015). China has the largest area of planted forests worldwide, with 36% (69 million ha) of the country's forests covered with forest plantations (Chinese Ministry of Forestry 2014). China has a long history of traditional practices in forestry. However, in the late 1980s, a large-scale afforestation programme was initiated to meet the commercial demand for high quality timber and other wood products (Wang et al. 2009). Within this framework, native forests were converted into monoculture tree plantations.

The successive planting of monoculture species at the same site often causes soil fertility to decline as the nutrients are largely utilised by fast-growing species (Kooch et al. 2016). Many studies have reported major decline in soil fertility and timber yield due to successive rotations of monoculture plantations (Bi et al. 2007, Zhang et al. 2009, Selvaraj et al. 2017). The concentration of available soil phosphorus declined between the first and second rotations of *Acacia auriculiformis* plantations in South Vietnam (Huong et al. 2015). In Chinese fir (*Cunninghamia lanceolata*) plantations in southern China, soil carbon and nitrogen declined by 15.3 and 12.4% respectively between the second and third rotations (Zhang et al. 2004).

Chinese fir is endemic to China, fast growing and is an evergreen coniferous tree cultivated for its high wood quality and commercial purposes such as for building construction and manufacturing furniture. The history of Chinese fir cultivation can be traced back to more than 1000 years (Wu 1984). Due to population increase, economic development and increasing demand for wood products, area under Chinese fir plantation rapidly increased to over 12 Mha in China (Chen et al. 2016). However, this increase was at the expense of natural forests, which were converted to monoculture and mixed plantations of Chinese fir. Chinese fir plantation covers 60–80% of the total forest area in the southeast provinces of China (Bi et al. 2007). Usually, mature Chinese fir timber stands are harvested at the age of 25–30 years old by clear-cutting followed by slash-and-burn (i.e. one rotation) but in recent times, timber is harvested after short rotation period (20–25 years) to meet the high demand. Current management practices include clear-cutting, slash burning and weeding twice a year in the first three years after planting followed by standard thinning practices (removal of alternate rows of branches and cutting of the crowns) at 10–13 years of age.

Only a few studies examined the effect of successive rotations of Chinese fir plantations on soil carbon, and they were limited to only three rotations of the species (Zhang et al. 2004, Zhang et al. 2009). Earlier investigations of soil nutrient dynamics in Chinese fir plantations were limited to chronosequence stand ages (Chen et al. 2013, Zhang et al. 2009, 2016, Zhou et al. 2015). This study investigated how soil nutrients are affected by the conversion of natural broadleaved forests to monoculture Chinese fir plantations over four rotations. The values were compared with soil nutrients of secondary natural broadleaved forest, which were used as baselines.

## MATERIALS AND METHODS

### Study area

The study area is located in a small watershed in Wangtai Town, Nanping City, Fujian Province, China (Figure 1). The region has a subtropical monsoon climate, with mean annual temperature of 19.3 °C and relative humidity of 83%. The mean annual precipitation is 1699 mm, with most of it occurring in March till August. Mean annual evapotranspiration is 1413 mm. The altitude of the study area ranges from 150–250 m while the slope is 30–40°. The soil is red earth derived from granite, equivalent to Hapludult. Soil texture at the site ranges from sandy clay to clay loam. Soil profile is well developed with charcoal deposition in the organic layer due to slash-and-burn management practices. Thickness of the soil profile is over 1 m and is characterised by the accumulation of clay and iron oxides. Only a few old stands were protected, with plantations dominated by young (~ 8 years) and mid-rotation age (~ 12 years) classes. A first generation stand of Chinese fir planted in 1919 in Nanping (the study area) is the oldest stand of Chinese fir in China.

### Chronosequence approach

Sampling was performed in the year 2015. A total of 12 sites were sampled. They consisted of four rotation sites with one slash-and-burn cultivation cycle (first rotation) of stands with 12, 21, 40 and 97 years old trees (which were the ages of the trees and consequently the times after the burning), four sites of a second rotation

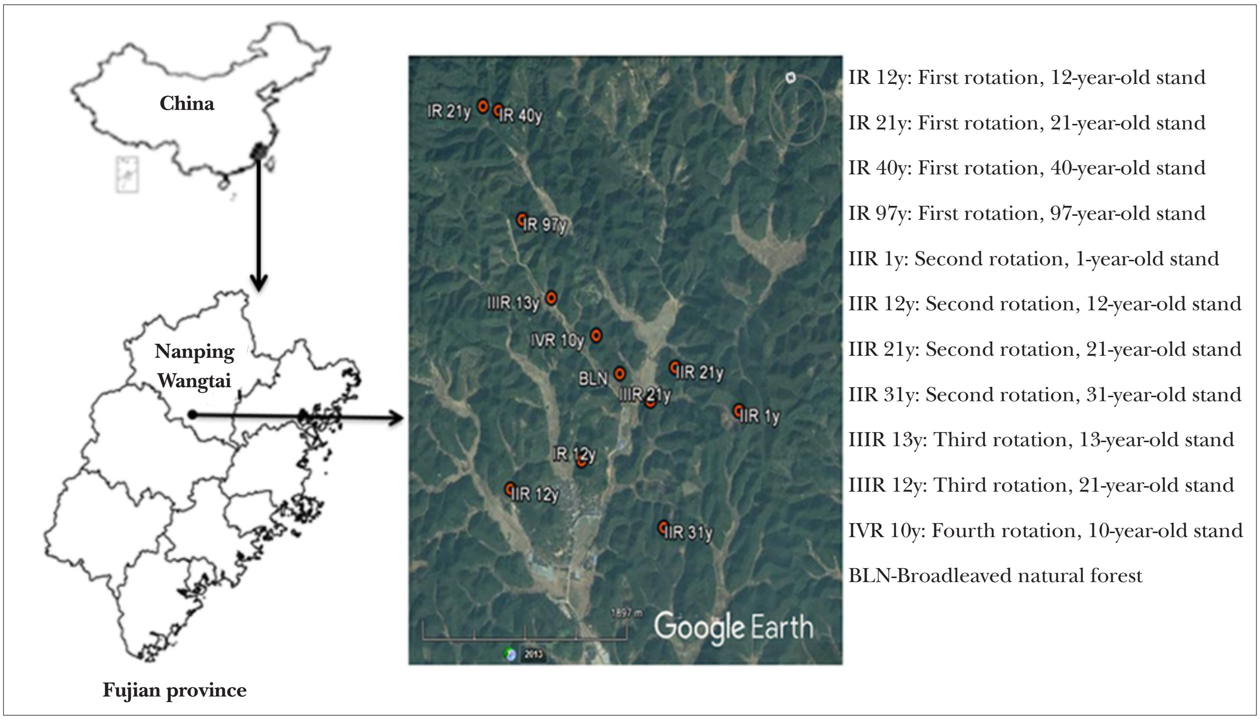


**Figure 1** Location map of the study area

(1, 12, 21 and 31 years old), two sites with three rotations (13 and 21 years old), and one site with four slash-and-burn cultivation rotation corresponding to Chinese fir of 10 years old. The selection of the sites occupied by trees of 12 (first, second and third rotations) and 10 years old (fourth rotation) was done to allow comparison of soil nutrients with similar period of time since the last burning, from one to four cycles of slash-and-burn, and a natural broadleaved forest. The average time that elapsed between each slash-and-burn cycle was 20 to 25 years. To minimise site variation, plantations having similar elevation, parent material, soil texture and topography were selected. The species that dominated the broadleaved forest were *Maesa japonica*, *Woodwardia japonica*, *Angiopteris fokiensis*, *Miscanthus floridulus* and *Dicranopteris dichotoma*. Main characteristics and topsoil properties of the selected sites are represented in Table 1.

## Soil sampling

Five sample plots (20 m × 20 m) were randomly selected from each of the 12 stands. In each plot, three pits were dug diagonally. From each pit, soil samples were collected at five depths of 0–20, 20–40, 40–60, 60–80 and 80–100 cm. Soils from the three sampling pits were mixed thoroughly to form a single composite sample for each soil layer and were sealed in airtight bags. A total of 300 mineral soil samples (five quadrats at the five specified depths) in 11 stands of different ages of Chinese fir and a secondary broadleaved forest (~ 40 years old) were collected and transferred to the laboratory for further analysis.

## Chemical analysis

Soil samples were air dried, ground, sieved (< 2 mm) and analysed for soil chemical properties. The samples were sieved through 0.14-mm mesh and analysed for total nitrogen (N), total phosphorus (P) and total potassium (K). Three replicates from each soil layer were taken for the analysis. Total N was determined by dry combustion method using CN elemental analyser. Nitrate-nitrogen ($NO_3^-$-N) and ammoniacal nitrogen ($NH_4^+$-N) were determined by continuous segmented flow analyser while hydrolysable nitrogen was determined using alkaline hydrolysis diffusion method. Total P and total K contents were determined using molybdenum–antimony colorimetric method. P concentrations were measured colorimetrically while total K was measured using flame photometer. Available P was analysed by Bray and Kurtz (1945) method. Available K was extracted using 1.0 N ammonium acetate (Schollenberger & Simon 1945) and determined by flame photometer.

## Statistical analysis

Two-way factorial ANOVA was performed to test for significant differences in soil nutrients between stand ages and soil sampling depths. The data were analysed after testing for homogeneity of variance using Levene's test. When constant variance was not satisfied, a log or square transformation was used. Multiple comparisons of the means of different soil nutrients between stand ages, rotations and soil sampling depths were performed using Tukey's HSD test ($p$ = 0.05). All statistical analyses were performed using SPSS 17.0 software.

# RESULTS

## Soil nutrient dynamics in successive rotations

Successive planting of Chinese fir caused significant decline in the concentrations of $NH_4^+$-N, total P, available P and available K in the surface soil layer (0–20 cm) from the first to fourth rotation (Table 2). In contrast, the amount of these nutrients increased from the third to fourth rotation in the deeper soil layers (> 40 cm).

## Characteristics of soil nutrients of stands of different ages

Concentration of soil nutrients decreased from 21- to 40-year-old stand. Mean difference in concentrations of total N (0.54 g $kg^{-1}$), hydrolysable N (51.42 mg $g^{-1}$), $NO_3^-$-N (17.58 mg $g^{-1}$), $NH_4^+$-N (3.88 mg $g^{-1}$), total P (0.19 g $kg^{-1}$), and available K (20.95 mg $g^{-1}$) increased from 40- to 97-year-old stand at 1-m depth. The 10-year-old stand of fourth rotation had the lowest concentration of $NO_3^-$-N (1.34 mg $g^{-1}$), $NH_4^+$-N (3.15 mg $g^{-1}$), total P (0.24 g $kg^{-1}$), available P (4.43 mg $g^{-1}$), total K (35.79 g $kg^{-1}$), and available K (61.53 mg $g^{-1}$) in the topsoil (0–20 cm) (Table 2).

**Table 1** Site characteristics and topsoil (0–20 cm) properties across the Chinese fir chronosequence and broadleaved natural forest in Nanping

| Site characteristic | Broadleaved | First rotation (year) | | | | Second rotation (year) | | | | Third rotation (year) | | Fourth rotation (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 12 | 21 | 40 | 97 | 1 | 12 | 21 | 31 | 13 | 21 | 10 |
| Mean elevation (m) | 212–245 | 206–248 | 219–235 | 216–238 | 212–240 | 215–245 | 216–238 | 215–243 | 218–237 | 216–239 | 214–244 | 218–242 |
| Aspect | South-east | | | | | | | | | | | |
| Slope (°) | 25–38 | 22–35 | 21–34 | 24–34 | 23–37 | 22–37 | 25–38 | 24–38 | 21–32 | 25–35 | 26–34 | 21–32 |
| Stem density ($ha^{-1}$) | 782 | 4225 | 3350 | 1542 | 825 | 1539 | 2392 | 2158 | 1818 | 3775 | 2516 | 2775 |
| Gravimetric water potential (%) | 45 | 33 | 37 | 32 | 35 | 36 | 39 | 30 | 34 | 31 | 34 | 38 |
| pH | 4.50 | 4.38 | 4.67 | 4.61 | 4.51 | 4.59 | 4.44 | 4.49 | 4.61 | 4.48 | 4.61 | 4.39 |

**Table 2** Concentrations of total and available forms of nitrogen (N), phosphorus (P) and potassium (K) in various soil depths and stand ages of Nanping

| Soil nutrient | Depth (cm) | Broadleaved | First rotation (year) | | | | Second rotation (year) | | | | Third rotation (year) | | Fourth rotation (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 12 | 21 | 40 | 97 | 1 | 12 | 21 | 31 | 13 | 21 | 10 |
| Total N (g $kg^{-1}$) | 0–20 | 1.91$^{a}$ | 1.85$^{aA}$ | 1.60$^{aAB}$ | 1.16$^{aB}$ | 1.47$^{aAB}$ | 1.57$^{aA}$ | 1.98$^{aA}$ | 1.70$^{aA}$ | 1.37$^{aA}$ | 1.58$^{aA}$ | 1.69$^{aA}$ | 1.46$^{a}$ |
| | 20–40 | 1.47$^{b}$ | 1.08$^{bB}$ | 1.35$^{bA}$ | 0.86$^{abB}$ | 0.91$^{bB}$ | 0.92$^{bA}$ | 1.11$^{bA}$ | 1.11$^{bA}$ | 0.83$^{bA}$ | 1.08$^{bA}$ | 1.11$^{bB}$ | 1.06$^{b}$ |
| | 40–60 | 1.23$^{bc}$ | 0.92$^{bA}$ | 0.89$^{cA}$ | 0.72$^{bA}$ | 0.77$^{bcA}$ | 0.76$^{bcA}$ | 0.95$^{bA}$ | 0.87$^{cA}$ | 0.67$^{cA}$ | 0.84$^{cA}$ | 0.93$^{bcB}$ | 0.89$^{bc}$ |
| | 60–80 | 0.92$^{c}$ | 0.79$^{bA}$ | 0.80$^{cA}$ | 0.64$^{bA}$ | 0.73$^{bcA}$ | 0.65$^{cA}$ | 0.80$^{bA}$ | 0.81$^{cA}$ | 0.64$^{cA}$ | 0.72$^{dA}$ | 0.81$^{cB}$ | 0.79$^{c}$ |
| | 80–100 | 0.87$^{c}$ | 0.83$^{bA}$ | 0.72$^{cAB}$ | 0.63$^{bB}$ | 0.67$^{cAB}$ | 0.61$^{cA}$ | 0.74$^{bA}$ | 0.78$^{cA}$ | 0.64$^{cA}$ | 0.70$^{dA}$ | 0.75$^{cB}$ | 0.76$^{c}$ |
| $NO_3^-$-N (mg $kg^{-1}$) | 0–20 | 7.49$^{a}$ | 2.51$^{aB}$ | 4.65$^{abB}$ | 2.63$^{aB}$ | 8.84$^{aA}$ | 6.33$^{aA}$ | 4.94$^{aA}$ | 7.53$^{aA}$ | 8.09$^{aA}$ | 1.19$^{aA}$ | 5.18$^{aB}$ | 1.34$^{a}$ |
| | 20–40 | 4.00$^{b}$ | 1.58$^{abB}$ | 2.98$^{bAB}$ | 1.50$^{bB}$ | 4.41$^{bA}$ | 3.89$^{aAB}$ | 4.74$^{bA}$ | 2.74$^{bB}$ | 3.45$^{bAB}$ | 1.52$^{aA}$ | 2.92$^{bB}$ | 1.31$^{a}$ |
| | 40–60 | 2.83$^{b}$ | 1.00$^{bB}$ | 1.91$^{bB}$ | 0.88$^{bB}$ | 3.52$^{bA}$ | 3.59$^{aA}$ | 3.79$^{cA}$ | 2.36$^{bA}$ | 2.71$^{bA}$ | 1.18$^{aA}$ | 2.57$^{bB}$ | 1.25$^{a}$ |
| | 60–80 | 2.42$^{b}$ | 0.81$^{bB}$ | 1.53$^{aB}$ | 1.22 $^{bB}$ | 4.47$^{bA}$ | 3.41$^{aA}$ | 3.48$^{dA}$ | 2.04$^{bA}$ | 2.74$^{bA}$ | 1.22$^{aA}$ | 2.75$^{bB}$ | 1.28$^{a}$ |
| | 80–100 | 2.53$^{b}$ | 0.88$^{bB}$ | 1.15$^{abB}$ | 1.14$^{bB}$ | 3.70$^{bA}$ | 4.92$^{aA}$ | 3.06$^{eA}$ | 1.92$^{bA}$ | 2.82$^{bA}$ | 1.43$^{aA}$ | 2.58$^{bB}$ | 1.26$^{a}$ |
| Soil nutrient | Depth (cm) | Broadleaved | First rotation (year) | | | | Second rotation (year) | | | | Third rotation (year) | | Fourth rotation (year) |
| | | | 12 | 21 | 40 | 97 | 1 | 12 | 21 | 31 | 13 | 21 | 10 |
| Hydrosable N (mg $kg^{-1}$) | 0–20 | 156.7$^{a}$ | 142.8$^{aA}$ | 147.5$^{aA}$ | 92.3$^{aB}$ | 121.3$^{aAB}$ | 114.9$^{aAB}$ | 136.9$^{aA}$ | 123.9$^{aB}$ | 110.9$^{aB}$ | 83.3$^{aA}$ | 124.9$^{aB}$ | 108.5$^{a}$ |
| | 20–40 | 101.29$^{b}$ | 87.53$^{bA}$ | 98.29$^{bA}$ | 59.3$^{bB}$ | 61.69$^{bB}$ | 56.29$^{bC}$ | 73.65$^{bB}$ | 85.88$^{bA}$ | 59.66$^{bC}$ | 51.48$^{bA}$ | 85.08$^{bB}$ | 72.37$^{b}$ |
| | 40–60 | 83.42$^{b}$ | 63.21$^{cA}$ | 61.28$^{cA}$ | 40.49$^{bcB}$ | 47.02$^{cB}$ | 46.71$^{bcAB}$ | 51.29$^{cA}$ | 57.76$^{cA}$ | 38.93$^{cB}$ | 35.84$^{cA}$ | 61.82$^{cB}$ | 60.32$^{c}$ |
| | 60–80 | 48.24$^{c}$ | 61.57$^{cA}$ | 38.83$^{cB}$ | 36.82$^{bcB}$ | 42.26$^{cB}$ | 33.85$^{cdB}$ | 39.38$^{cAB}$ | 45.75$^{dA}$ | 33.39$^{cdB}$ | 28.44$^{cdA}$ | 46.3$^{cB}$ | 48.61$^{cd}$ |
| | 80–100 | 40.45$^{c}$ | 41.80$^{cA}$ | 37.21$^{cAB}$ | 29.74$^{cB}$ | 37.87$^{aAB}$ | 31.02$^{dA}$ | 33.41$^{cA}$ | 37.09$^{eA}$ | 30.78$^{dA}$ | 24.18$^{dA}$ | 42.37$^{cB}$ | 43.64$^{d}$ |
| $NH_4^+$-N (mg $kg^{-1}$) | 0–20 | 4.99$^{a}$ | 6.65$^{aA}$ | 5.39$^{aB}$ | 4.72$^{aB}$ | 5.14$^{aB}$ | 4.80$^{aA}$ | 6.01$^{aA}$ | 6.79$^{aA}$ | 6.31$^{aA}$ | 3.88$^{aA}$ | 6.88 $^{aB}$ | 3.15$^{a}$ |
| | 20–40 | 3.65$^{b}$ | 3.98$^{bB}$ | 4.64$^{aAB}$ | 3.88$^{bB}$ | 4.93$^{aB}$ | 4.13$^{abB}$ | 2.59$^{bC}$ | 5.14$^{bA}$ | 4.31$^{bAB}$ | 2.51$^{bA}$ | 4.59$^{bB}$ | 2.49$^{b}$ |
| | 40–60 | 3.46$^{b}$ | 3.56$^{bcB}$ | 3.20$^{aB}$ | 3.33$^{bcB}$ | 4.28$^{bA}$ | 4.10$^{abAB}$ | 2.37$^{bC}$ | 4.74$^{bA}$ | 3.58$^{bB}$ | 2.54$^{bA}$ | 4.10$^{bB}$ | 2.88$^{ab}$ |
| | 60–80 | 3.18$^{b}$ | 2.92$^{bB}$ | 2.74$^{aB}$ | 3.07$^{cB}$ | 4.12$^{bA}$ | 3.72$^{bAB}$ | 2.04$^{bC}$ | 3.80$^{bcA}$ | 3.23$^{bB}$ | 2.18$^{bA}$ | 3.28$^{bB}$ | 2.88$^{ab}$ |
| | 80–100 | 3.34$^{b}$ | 3.28$^{bcA}$ | 2.52$^{aB}$ | 3.25$^{bcA}$ | 3.67$^{bA}$ | 3.23$^{bA}$ | 2.20$^{cB}$ | 3.35$^{dA}$ | 3.11$^{bA}$ | 2.34$^{bA}$ | 3.40$^{bB}$ | 2.70$^{ab}$ |

(continued)

**Table 2** (continued)

| Soil nutrient | Depth (cm) | Broadleaved | First rotation (year) | | | | Second rotation (year) | | | | Third rotation (year) | | Fourth rotation (year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 12 | 21 | 40 | 97 | 1 | 12 | 21 | 31 | 13 | 21 | 10 |
| Total P (g kg$^{-1}$) | 0–20 | 0.39$^{a}$ | 0.32$^{aB}$ | 0.30$^{aC}$ | 0.31$^{aBC}$ | 0.36$^{aA}$ | 0.34$^{aB}$ | 0.30$^{aB}$ | 0.32$^{aC}$ | 0.37$^{aA}$ | 0.28$^{aA}$ | 0.26$^{aB}$ | 0.24$^{a}$ |
| | 20–40 | 0.30$^{b}$ | 0.27$^{bA}$ | 0.25$^{bA}$ | 0.20$^{bcB}$ | 0.29$^{bA}$ | 0.30$^{bA}$ | 0.29$^{bA}$ | 0.26$^{bB}$ | 0.24$^{bB}$ | 0.24$^{bA}$ | 0.19$^{bB}$ | 0.19$^{b}$ |
| | 40–60 | 0.26$^{c}$ | 0.24$^{cA}$ | 0.19$^{cB}$ | 0.22$^{bAB}$ | 0.24$^{cA}$ | 0.22$^{cA}$ | 0.22$^{cA}$ | 0.19$^{cB}$ | 0.18$^{cB}$ | 0.17$^{cA}$ | 0.15$^{cB}$ | 0.19$^{c}$ |
| | 60–80 | 0.22$^{d}$ | 0.20$^{dA}$ | 0.18$^{cB}$ | 0.18$^{cB}$ | 0.19$^{dB}$ | 0.19$^{dA}$ | 0.15$^{dB}$ | 0.15$^{dB}$ | 0.14$^{dB}$ | 0.14$^{dA}$ | 0.12$^{dB}$ | 0.15$^{d}$ |
| | 80–100 | 0.19$^{e}$ | 0.16$^{eA}$ | 0.12$^{dB}$ | 0.12$^{dB}$ | 0.14$^{eA}$ | 0.15$^{eA}$ | 0.12$^{eB}$ | 0.10$^{eC}$ | 0.09$^{eC}$ | 0.10$^{e\,A}$ | 0.08$^{e\,B}$ | 0.11$^{e}$ |
| Available P (mg kg$^{-1}$) | 0–20 | 15.27$^{a}$ | 8.72$^{a\,A}$ | 9.80$^{abA}$ | 8.06$^{aA}$ | 8.58$^{aA}$ | 7.34$^{aB}$ | 6.79$^{a\,B}$ | 9.26$^{aA}$ | 6.80$^{aB}$ | 6.15$^{a\,A}$ | 8.79$^{aB}$ | 4.43$^{b}$ |
| | 20–40 | 12.27$^{b}$ | 8.53$^{abAB}$ | 11.07$^{aA}$ | 7.49$^{aB}$ | 6.93$^{abB}$ | 6.43$^{abA}$ | 6.31$^{aA}$ | 8.07$^{abA}$ | 7.80$^{aA}$ | 4.54$^{bA}$ | 8.59$^{bB}$ | 3.24$^{c}$ |
| | 40–60 | 10.68$^{c}$ | 8.17$^{abA}$ | 7.03$^{bcA}$ | 7.52$^{aA}$ | 6.20$^{bcA}$ | 4.66$^{bcB}$ | 6.92$^{aA}$ | 6.99$^{bA}$ | 7.20$^{aA}$ | 3.62$^{bA}$ | 8.20$^{abB}$ | 5.67$^{a}$ |
| | 60–80 | 9.49$^{d}$ | 7.39$^{bA}$ | 6.11$^{bcAB}$ | 6.56$^{aA}$ | 4.36$^{cB}$ | 3.84$^{cB}$ | 5.36$^{aB}$ | 5.32$^{cB}$ | 8.37$^{aA}$ | 3.15$^{bA}$ | 8.15$^{abB}$ | 4.45$^{b}$ |
| | 80–100 | 8.47$^{e}$ | 7.50$^{bA}$ | 4.20$^{cB}$ | 6.22$^{aAB}$ | 4.82$^{bcB}$ | 4.06$^{bcB}$ | 5.69$^{aB}$ | 5.33$^{cB}$ | 8.05$^{aA}$ | 3.33$^{bA}$ | 7.25$^{cB}$ | 4.72$^{b}$ |
| Total K (g kg$^{-1}$) | 0–20 | 65.81$^{a}$ | 57.04$^{aB}$ | 60.61$^{aA}$ | 51.76$^{aC}$ | 49.63$^{aD}$ | 60.77$^{aA}$ | 54.59$^{aC}$ | 52.04$^{aD}$ | 58.29$^{aB}$ | 41.99$^{aA}$ | 39.50$^{aB}$ | 35.79$^{a}$ |
| | 20–40 | 63.09$^{b}$ | 51.98$^{bB}$ | 56.88$^{bA}$ | 49.55$^{bC}$ | 46.79$^{bD}$ | 56.84$^{bA}$ | 50.56$^{bC}$ | 49.34$^{bD}$ | 55.58$^{bB}$ | 40.68$^{bA}$ | 38.05$^{bB}$ | 31.84$^{b}$ |
| | 40–60 | 60.59$^{c}$ | 48.19$^{cB}$ | 50.65$^{cA}$ | 44.19$^{cC}$ | 41.83$^{cD}$ | 55.48$^{cA}$ | 48.10$^{cC}$ | 44.26$^{cD}$ | 51.75$^{cB}$ | 38.03$^{cA}$ | 32.95$^{c\,B}$ | 38.31$^{c}$ |
| | 60–80 | 56.69$^{d}$ | 42.35$^{dB}$ | 47.98$^{dA}$ | 40.56$^{dC}$ | 38.08$^{dD}$ | 50.46$^{dA}$ | 45.54$^{dC}$ | 39.24$^{dD}$ | 48.04$^{dB}$ | 35.56$^{dA}$ | 30.55$^{dB}$ | 39.81$^{d}$ |
| | 80–100 | 53.15$^{e}$ | 40.76$^{eB}$ | 44.46$^{eA}$ | 39.38$^{eC}$ | 36.88$^{eD}$ | 48.13$^{eA}$ | 44.38$^{eC}$ | 38.00$^{eD}$ | 45.65$^{eB}$ | 33.11$^{eA}$ | 29.36$^{e\,B}$ | 36.30$^{e}$ |
| Available K (mg kg$^{-1}$) | 0–20 | 94.08$^{a}$ | 64.32$^{aC}$ | 71.13$^{aB}$ | 76.68$^{aA}$ | 78.95$^{aA}$ | 84.38$^{aA}$ | 77.0$^{aC}$ | 79.31$^{aBC}$ | 81.09$^{aB}$ | 65.33$^{aA}$ | 67.37$^{aB}$ | 61.53$^{a}$ |
| | 20–40 | 86.62$^{b}$ | 54.94$^{bC}$ | 64.35$^{bB}$ | 70.15$^{bA}$ | 70.66$^{bA}$ | 76.33$^{bA}$ | 72.29$^{bC}$ | 72.08$^{bC}$ | 73.32$^{bBC}$ | 62.90$^{aA}$ | 63.40$^{bB}$ | 58.33$^{b}$ |
| | 40–60 | 82.83$^{c}$ | 48.76$^{cC}$ | 56.08$^{cB}$ | 56.59$^{cAB}$ | 60.12$^{cA}$ | 69.27$^{cA}$ | 66.74$^{cAB}$ | 65.73$^{cB}$ | 62.10$^{cC}$ | 59.64$^{bA}$ | 57.86$^{cB}$ | 61.05$^{c}$ |
| | 60–80 | 77.58$^{d}$ | 43.07$^{dB}$ | 52.13$^{dA}$ | 42.32$^{dB}$ | 49.62$^{dA}$ | 65.02$^{dA}$ | 64.26$^{cdA}$ | 59.93$^{dB}$ | 55.86$^{dC}$ | 55.11$^{cA}$ | 53.80$^{dB}$ | 58.51$^{d}$ |
| | 80–100 | 76.31$^{d}$ | 40.93$^{dB}$ | 45.49$^{eA}$ | 37.38$^{eC}$ | 44.72$^{eA}$ | 62.16$^{dA}$ | 61.78$^{dA}$ | 55.91$^{eB}$ | 52.05$^{eC}$ | 51.58$^{dA}$ | 49.80$^{eB}$ | 55.72$^{e}$ |

Different lower case letters indicate statistical significance ($p < 0.05$) at different soil depths, different upper case letters indicate statistical significance ($p < 0.05$) at the same soil layer at different stand ages

## Depth distribution of soil nutrients

Surface soil (0–20 cm) accumulated maximum soil nutrients in stands of all ages, except for available P. Concentrations of total P, total K, hydrolysable N and available K decreased with increasing soil depth. There was significant ($p < 0.05$) and constant decrease in total K concentration with decrease in soil depth (Table 2). Except for total N, soil depth and its interaction with stand age had significant effect on the concentration of soil nutrients in all three rotations (Table 3).

## Conversion of natural forest to monoculture plantation

The conversion of natural broadleaved forest to a monoculture plantation affected the concentration of total and available forms of N, P and K. Successive rotations of Chinese fir plantations caused a decline (fourth rotation) in total N (22.5%), $NO_3^-$-N (66.5%), $NH_4^+$-N (24.2%), hydrolysable N (22.4%), total P (43.5%), available P (59.9%), total K (50.5%) and available K (35.2%) at the total depth of 1 m when compared with the broadleaved forest.

**Table 3** Comparison of effects of stand age and soil depth on soil nutrients in Chinese fir stands including all stand ages at given the rotation using two-way ANOVA

| Soil nutrient | Stand age | | Soil depth | | Soil depth × stand age | | |
|---|---|---|---|---|---|---|---|
| | F | p | F | p | F | p | $r^2$ |
| First rotation | | | | | | | |
| Total N | 14.14 | < 0.05 | 66.22 | < 0.05 | 1.93 | < 0.05 | 0.805 |
| $NO_3^-$-N | 65.70 | < 0.05 | 16.29 | < 0.05 | 5.72 | < 0.05 | 0.648 |
| $NH_4^+$-N | 8.54 | < 0.05 | 18.32 | < 0.05 | 8.46 | < 0.05 | 0.527 |
| Hydrolysable N | 21.96 | < 0.05 | 135.82 | < 0.05 | 2.89 | 0.001 | 0.782 |
| Total P | 38.99 | < 0.05 | 365.38 | < 0.05 | 5.21 | < 0.05 | 0.901 |
| Available P | 7.49 | < 0.05 | 17.63 | < 0.05 | 2.93 | 0.001 | 0.416 |
| Total K | 6105.9 | < 0.05 | 10,686.2 | < 0.05 | 60.54 | < 0.05 | 0.997 |
| Available K | 96.21 | < 0.05 | 641.38 | < 0.05 | 15.09 | < 0.05 | 0.944 |
| Second rotation | | | | | | | |
| Total N | 17.25 | < 0.05 | 123.89 | < 0.05 | 1.33 ns | 0.216 ns | 0.876 ns |
| $NO_3^-$-N | 2.49 ns | 0.06 ns | 23.99 | < 0.05 | 2.43 | 0.006 | 0.424 |
| $NH_4^+$-N | 17.66 | < 0.05 | 40.02 | < 0.05 | 2.23 | 0.01 | 0.571 |
| Hydrolysable N | 19.36 | < 0.05 | 351.31 | < 0.05 | 2.29 | 0.01 | 0.892 |
| Total P | 61.72 | < 0.05 | 1323.02 | < 0.05 | 11.22 | < 0.05 | 0.969 |
| Available P | 17.57 | < 0.05 | 8.83 | < 0.05 | 3.97 | < 0.05 | 0.430 |
| Total K | 12876.1 | < 0.05 | 15,044.5 | < 0.05 | 164.4 | < 0.05 | 0.998 |
| Available K | 60.76 | < 0.05 | 519.55 | < 0.05 | 9.66 | < 0.05 | 0.930 |
| Third rotation | | | | | | | |
| Total N | 4.69 | 0.03 | 98.71 | < 0.05 | 0.24 ns | 0.912 ns | 0.909 ns |
| $NO_3^-$-N | 125.5 | < 0.05 | 8.01 | < 0.05 | 9.77 | < 0.05 | 0.686 |
| $NH_4^+$-N | 109.52 | < 0.05 | 32.01 | < 0.05 | 4.63 | 0.002 | 0.740 |
| Hydrolysable N | 97.45 | < 0.05 | 109.61 | < 0.05 | 3.04 | 0.021 | 0.835 |
| Total P | 103.59 | < 0.05 | 550.37 | < 0.05 | 5.097 | 0.001 | 0.959 |
| Available P | 273.67 | < 0.05 | 9.93 | < 0.05 | 2.65 | 0.03 | 0.783 |
| Total K | 4989.02 | < 0.05 | 4544.6 | < 0.05 | 107.16 | < 0.05 | 0.996 |
| Available K | 1.62 ns | 0.205 ns | 146.50 | < 0.05 | 2.87 | 0.02 | 0.869 |

Results of the fourth generation cannot be compared due to the absence of multiple stand age; ns indicates non-significant difference between stand ages or soil depths (p = 0.05)

## DISCUSSION

### Effect of successive rotation on soil nutrients

Successive rotation of Chinese fir monoculture plantations caused concentrations of soil nutrients in the top soil (0–20 cm) to decline, as reported by Xi et al. (2009), Ma et al. (2007) and Wei et al. (2012). Decline in soil nutrients causes soil fertility to decline. Stands in the fourth rotation accumulated higher amounts of nutrients in the deeper layers (> 40 cm) than surface layers (0–40 cm) when compared with stands in the third rotation, except for hydrolysable N and $NO_3^-$-N. This indicated that more rotations might not necessarily cause soil nutrients to decline in the deeper soil layers (up to 1 m). In Chinese fir plantations, subsurface soil layers had higher nutrient concentration than surface layers even at the fourth rotation. This could be attributed to the exposure of the surface layer as a result of repeated slash-and-burn treatment resulting in the removal of ground vegetation and organic matter, causing loss of soil nutrients. Nutrients from the surface layers (0–40 cm) are also taken up by the Chinese fir during their early stage of development. In contrast, large dry matter root systems from previous rotations remain in the deeper soil layer (because they were not uprooted), which serve as nutrient-rich stores (Wang et al. 2013).

### Dynamics of soil nutrients at different stand ages

In the first rotation, availability of total K and different forms of N ($NO_3^-$-N and hydrolysable N) and P increased from 12- to 21-year-old stands but then declined in 40-year-old stand. Our results suggested that cutting cycles of Chinese fir should not be implemented in stands of < 20 years of age. Since we did not have access to stands of 22–29 years of age, we could not establish an exact age for optimal harvesting after 21-years based on changes in soil nutrient levels. However, clear-harvesting should be delayed a further ~5 years at sites where Chinese fir plantations are continuously cultivated with clear-cutting at ~20–25 years (Ma et al. 2007, Tian et al. 2011). Moreover, our study showed that the 97-year-old stand accumulated more soil nutrients (such as total N, $NO_3^-$-N, hydrolysable N, total P and available K) than the 40-year-old stand. This difference is likely due to the fact that old growth plantations sequester more nutrients through more litter input and understorey vegetation (Zhou et al. 2006, Luyssaert et al. 2008). Compared with 12-year-old stand, the total and inorganic forms of N were lower in 1-year-old stand, where the site was clear-cut and slash-and-burned. This phenomenon occurred because stem and wood removal during clear-cutting and controlled slash burning significantly reduced nitrogen levels due to higher temperatures (Guo et al. 2010).

### Nutrient dynamics at different soil depths

Soil depth and stand age significantly affected soil nutrients in the first three rotations, except for total N in the second and third rotations. We also recorded significant decline in soil nutrients with increasing soil depth in stands of all ages, supporting the results of Groppo et al. (2015) and Breulmann et al. (2016) who documented this phenomenon regardless of plantation species, landuse and vegetation type. This decline in soil nutrient concentration is due to deposition of large amount of plant litter and its decomposition by soil fauna, resulting in more soil nutrients accumulating in the top soil compared with lower soil layers.

### Comparison of the broadleaved forest with monoculture plantation

Total and available forms of soil nutrients were higher in the broadleaved forest compared with all monoculture Chinese fir stands. This difference was due to more biomass accumulating in the soil from the understorey vegetation and broadleaved litter, which was also suggested by Chen et al. (2004) and Wan et al. (2013). Cultivation of selected broadleaved species reduces alleo-chemicals levels (Xia et al. 2016). Thus, the presence of broadleaved stands within Chinese fir monoculture could help improve soil properties and enhance wood production.

### Recommendations and perspectives for forest management

Understanding how soil nutrients are affected by current landuse practices is useful to help forest managers design appropriate conservation strategies to enhance forest productivity, maintain soil fertility and provide economic and ecological benefits. Such knowledge will also help clarify how timber yield and soil fertility are linked to soil nutrient levels. A number of inappropriate management practices such as monoculture plantations, high planting density, continuous rotation, slash burning and clear-cutting are likely to have negative impacts on soil fertility during the early stages of plant development.

In southern China, where most forest lands have been converted to plantations, it is essential to balance both ecological and economic benefits by defining the optimal number of rotations and harvest age of plantations. As most of the studies on Chinese fir plantations are limited to only three rotation cycles, further studies are necessary for drawing conclusions regarding the relationship between the number of rotation cycles and age of Chinese fir plantation.

The results of our study could be used to evaluate current management practices for Chinese fir plantations. Successive rotations of Chinese fir at the same site caused soil nutrients to decline, especially in the top soil. Thus, the site should not be planted with Chinese fir again after one or two rotations of the species. Instead, intercropping with annual plants should be implemented, or mixed planting of firs with broadleaved species. Concentration of soil nutrients increased in the deeper soil layer during the fourth rotation compared with the third rotation. The concentration of soil nutrients increased with increasing stand age. Except for total and available K, the concentrations of soil nutrients in the topsoil decreased from 21- to > 30-year-old stands in the first and second rotations. Thus, harvesting trees of ≤ 20 years in age is not an ecologically appropriate management strategy. Except for fourth rotation, the concentrations of soil nutrients declined with increasing depth in stands of all ages. Hence, the current management practices conducted in the study area such as clear-cutting, slash burning, and site preparation during the post-harvest stages, should be modified to avoid the depletion of soil nutrients and to improve soil fertility.

In conclusion, our study demonstrated that the successive planting of Chinese fir on the same site should be avoided, as this practice caused soil nutrients to decline. In our study, 40- and 31-year-old stands had lower concentrations of soil nutrients than the 21-year-old stand in the corresponding rotation. Thus, concentrations of soil nutrients in Chinese fir plantations could be sustained by increasing the stand age from 25 years but not more than 30 years. Stands should be grown for approximately 5 more years at sites that are currently managed by clear-harvesting at ~20–25 years (Ma et al. 2007, Tian et al. 2011). Thus, we suggest that current management practices should be revised to only two rotations and to harvest trees only between 25 and 30 years of age. Since soil fertility declined during forest conversion from natural broadleaved forest to Chinese fir plantations, we recommend mixing conifer plantations with selected broadleaved species for the effective sustainable management and to maintain soil fertility, which would generate both economic and environmental benefits to the plantation industry.

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