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Influence of long-term successive rotations and stand age of Chinese fir (*Cunninghamia lanceolata*) plantations on soil properties

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ABSTRACT

Tree plantations contribute towards balancing global carbon (C) and nitrogen (N) cycles, with the C:N ratio being a key factor determining soil fertility in plantations. In the present study, we investigated how the management practices of Chinese fir (*Cunninghamia lanceolata*) plantations affect soil organic carbon (SOC), C:N ratio and soil quality. We assessed how these soil properties vary for stands of (1) different ages (up to 97 years) within the same rotation and (2) similar ages but in different rotations (up to four). Soil samples were collected and analysed from incremental depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm). Continuous replanting of Chinese fir at the same site caused SOC stock and C:N ratio to decline after the second rotation. SOC stock (0–100 cm) decreased by 3, 3.6, and 14.3% between the first and second, second and third, and third and fourth rotations, respectively. The SOC concentration and C:N ratio declined from 21- to 40-year-old stands, and then increased in the 97-year-old stand throughout all soil depths. The stratification ratio (SR) index of SOC stock showed that continuous cultivation causes soil quality to decrease with increasing rotation cycle. Approximately 35–45% of equivalent soil mass SOC stocks were distributed in the upper soil layer (0–20 cm) in stands of all ages, indicating more organic C accumulation in the surface layer compared to subsurface layers (> 20 cm). In conclusion, we recommend that (1) cutting cycles of the stands should be increased from 20 to 25 years (current practice) to ~30 years of age and (2) plantations should only be cultivated to the second rotation to maintain site productivity, which would maximise both the ecological and economic value of this practice to the environment.

1. Introduction

Soil organic carbon (SOC) and nitrogen (N) influence plant growth and productivity in terrestrial ecosystems. On global scale, 383 Pg of soil C (Pan et al., 2011) and 133–140 Pg of soil N (Batjes, 1996) are stored within top 1 m of the soil depth. In China, SOC and N accumulates in the surface layer (0–20 cm) at an average rate of 366.7 and 21.1 kg ha^{-1} $year^{-1}$ respectively (Zhang et al., 2010; Liu et al., 2013).

Several indicators have been proposed to evaluate soil quality (Doran and Jones, 1996; Qi et al., 2009; Armenise et al., 2013; Vasu et al., 2016). Quiroga et al. (2005) suggested that SOC is the best indicator of soil quality and soil productivity. In comparison, Franzluebbers (2002) suggested using the stratification ratio (SR) to evaluate soil quality, because of the importance of understanding the depth distribution of soil properties. SR is defined as "the ratio of a soil property at the surface layer to that at a deeper layer". It is a good indicator of SOC stock because it can be used to infer the rate and amount of SOC accumulation (Moreno et al., 2006; Fernandez-Romero et al., 2016). Higher SR indicates undisturbed soil and high soil quality (Lozano-Garcia et al., 2016). Increased SR can be related to the rate and amount of SOC sequestration. Conversely, SR < 2 is common in degraded soils (Franzluebbers, 2002).

The vertical distribution of the C:N ratio influences how soils respond to changes in their use and management (Callesen et al., 2007). Marty et al. (2017) reported that the C:N ratio decreases with soil depth in the forests of eastern Canada. However, there is limited knowledge about how C:N ratios change after natural forests are converted to plantations and subjected to many rotation cycles. Thus, it is necessary to investigate how SOC and the C:N ratio change across successive rotation cycles of commercial tree plantations to elucidate potential economic and environmental impacts of this practice. In particular, this study stresses the importance of studying SOC and the C:N ratio in soil control sections (1 m depth) to understand how plantations influence the dynamics of large SOC stocks present in the subsoil (Lorenz and Lal,

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2005; Hobley and Wilson, 2016; Vasu et al., 2016). Furthermore, the importance of sampling deep in the soil layer (i.e. 1 m) to evaluate soil C accurately has been highlighted (Harper and Tibbett, 2013; Rumpel and Kogel-Knabner, 2010). However, changes in soil quality related to equivalent soil mass (*esm*) and SOC stock in the forest plantations of China remain poorly documented. For instance, a few studies have shown that SOC content declines up to a depth of 60 cm with increase in the number of rotations in subtropical regions of China (Fang, 1987; Shao, 1992; Zhang et al., 2004; Jian et al., 2009).

Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) is an endemic, evergreen coniferous species that is cultivated as a commercial tree. In southern China, only a few old stands of Chinese fir are protected, with plantations being dominated by young (~6 years) and mid-rotation (~12 years) age classes. A first-generation stand planted in 1919 in Nanping (the study area) is the oldest stand of Chinese fir in China. Here, we aimed to investigate how different rotations of Chinese fir plantations affect SOC and the C:N ratio. Specifically, we examined the dynamics of soil quality with respect to SOC stock of a Chinese fir plantation containing stands of (1) different stand ages (up to 97 years) within the same rotation and (2) similar stand ages but in different rotations (up to four). Our results are expected to provide information on the optimal number of rotations to maintain soil health, providing both economic benefits to plantation management and environmental benefits.

2. Materials and methods

2.1. Study area

The study area is located in a small watershed in Wangtai Town, Nanping City, Fujian Province, China (Fig. 1). This region has a subtropical monsoon climate, with a mean annual temperature of 19.3 °C and a relative humidity of 83% (Guo et al., 2014). The mean annual precipitation is 1699 mm, with most precipitation occurring from March to August. The mean annual evapotranspiration is 1413 mm. The altitude of the study area ranges from 150 to 250 m above mean sea level and the slope is ~30–40°. The soil is red earth derived from granite (Guo et al., 2005), equivalent to Hapludult based on United States Department of Agriculture (USDA) soil taxonomy (Soil Survey Staff, 2014). The soil texture of the sample site ranged from sandy clay to clay loam. The soil profile was well developed with charcoal deposition in the organic layer, due to slash burn management practices. The thickness of the A horizon ranged from ~10 to 20 cm, whereas that of the B horizon was characterised by accumulation of clay and iron oxides. The main characteristics and topsoil properties of the studied sites are presented in Table 1.

Mature timber of Chinese fir plantations is harvested by clear-cutting, followed by burning of the bark and residues. This practice influences soil CO_2 flux and alters the stability of organic carbon (Song et al., 2013). This practice also modifies C cycling by incorporating pyrogenic matter, like charcoal, in the surface and subsurface soil horizons. Traditionally, coarse roots were excavated and burned after tree cutting, and the abandoned site is used for intercropping with annual crops before replanting. Plantations are primarily restricted to slopes and, after one or two rotation, allowed to regenerate naturally by stump sprouting or natural seeding. This regeneration phase serves as a fallow period, helping to restore soil fertility at the site (Yu, 1997). Weeding is conducted 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. The ideal rotation period for Chinese fir is 25–30 years, but currently it has been shortened to ~20–25 years (Tian et al., 2011).

2.2. Experimental techniques

2.2.1. Chronosequence approach

In 2015, 11 Chinese fir stands of different ages (12-, 21-, 40-, and 97-year-old stands in the first rotation; 1-, 12-, 21-, and 31-year-old stands in the second rotation; 13- and 21-year-old stands in the third rotation; 10-year-old stand in the fourth rotation) were selected for the study. The stand age in each rotation was carefully selected to be as similar as possible across rotations to compare the soil carbon storage of similarly aged stands. For instance, we used 12- (first and second rotation), 13- (third rotation), and 10- (fourth rotation) year-old stands as similarly aged stands (~12-year-old stands) across four rotations. To minimise variation among sites, plantations which close each other were selected.

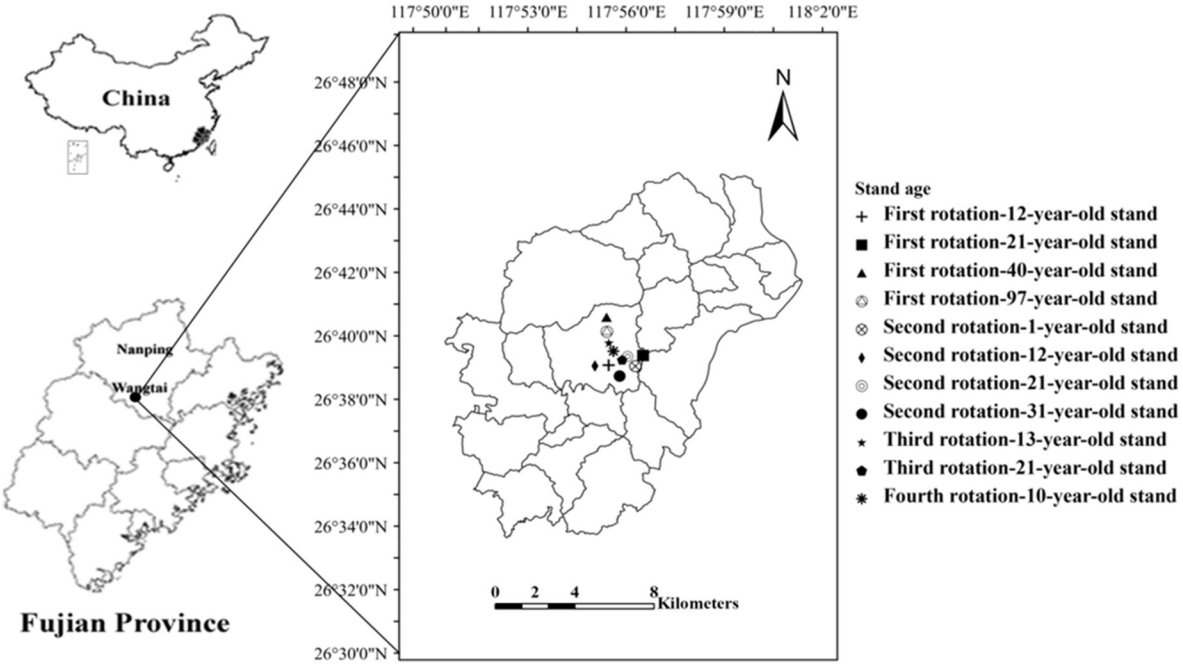

Fig. 1. Map of sampling locations of Chinese fir (*Cunninghamia lanceolata*) plantations of varying rotations and stand ages.