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Original Articles

Identification of indicators for evaluating and monitoring the effects of Chinese fir monoculture plantations on soil quality

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ABSTRACT

Globally, forest conversion is known to affect soil quality. In the present study, we developed a soil quality index (SQI) to quantify the changes in soil quality due to conversion of native forests into Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) plantations in southern China. We selected 11 Chinese fir stands of different ages (12-, 21-, 40-, and 97-year-old 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; and a 10-year-old stand in the fourth rotation) from sub-tropical forest plantations in Nanping, Fujian Province, China. Soil samples were collected from different depths (0–20, 20–40, 40–60, 60–80, and 80–100 cm) and 20 soil properties were analysed. SQI was computed from the minimum data set derived from principal component analysis (PCA). Although the PCA included many soil properties, we identified total phosphorus (TP) and labile carbon pool II (LP-II-C) as key soil quality indicators, because they contributed 36.2 and 34.9% to SQI, respectively, followed by labile nitrogen pool I (LP-I-N) and soil pH. SQI values showed that continuous replanting of Chinese fir at the same site decreased soil quality significantly at 0–100 cm depth. Increasing rotation cycle (from first to fourth) strongly reduced LP-II-C (48.8%), LP-I-N (56.6%), labile nitrogen-II (70.2%), nitrate-nitrogen (67.7%), and available phosphorus (48.4%), indicating that successive rotation degrades soil quality. Thus, our results demonstrate that Chinese fir cultivation should be limited to only two rotations in the same site to preserve soil quality. We conclude that TP, LP-II-C, LP-I-N, and pH can be used as effective indicators in temporal soil quality monitoring programs under forest plantations.

1. Introduction

Global plantation forests are estimated to cover an area of 264 million ha, corresponding to 6.6% of total forest area (FAO, 2010). China has the largest area of planted forests, with 69 million ha of tree plantations covering 36% of the forest land. The annual timber consumption increased by 7.2% from 2009 to 2015, and the timber stock volume increased by 35.8 $m^3\ ha^{-1}$ each year over the same period, with an average annual harvest of 283 million m^3 (Chinese Ministry of Forestry, 2014). Moreover, China is the largest consumer of wood in the world, as it imports more than 50% of timber and timber products traded globally. It is predicted that the timber requirement will be ~8.5–9.5 billion m^3 in 2020 due to rapidly growing national demand (Xie et al., 2011). In southern China, large areas of native forests have been converted into either pure or mixed plantations of Chinese fir, *Cunninghamia lanceolata*, and Moso bamboo, *Phyllostachys edulis*, to meet the increasing demand for timber products (Yang et al., 2009; Guan et al., 2015).

Chinese fir is an endemic, fast growing, evergreen coniferous tree, cultivated for its high wood quality and for its applications for commercial purposes, such as construction, manufacturing furniture, and biomass energy (Yu, 1997; Li et al., 2013). The history of Chinese fir cultivation can be traced back more than 1000 years (Wu, 1984). Due to increasing human populations, economic development, and increasing demand for wood products, the area under Chinese fir cultivation has rapidly increased and currently covers over 12 million ha in China (Chen et al., 2016). However, this increase has been at the expense of natural forests, as these have been converted to monoculture or mixed plantations of Chinese fir and Moso bamboo. Such plantations have widely expanded, and they presently cover 60–80% of the total area of timber plantations in the southeast provinces of China (Bi et al., 2007). Because of continuous cultivation of Chinese fir without adequate fallow periods, the production started to decrease in the 1980s due to soil and ecosystem degradation (Ma et al., 2007; Wang et al., 2014).

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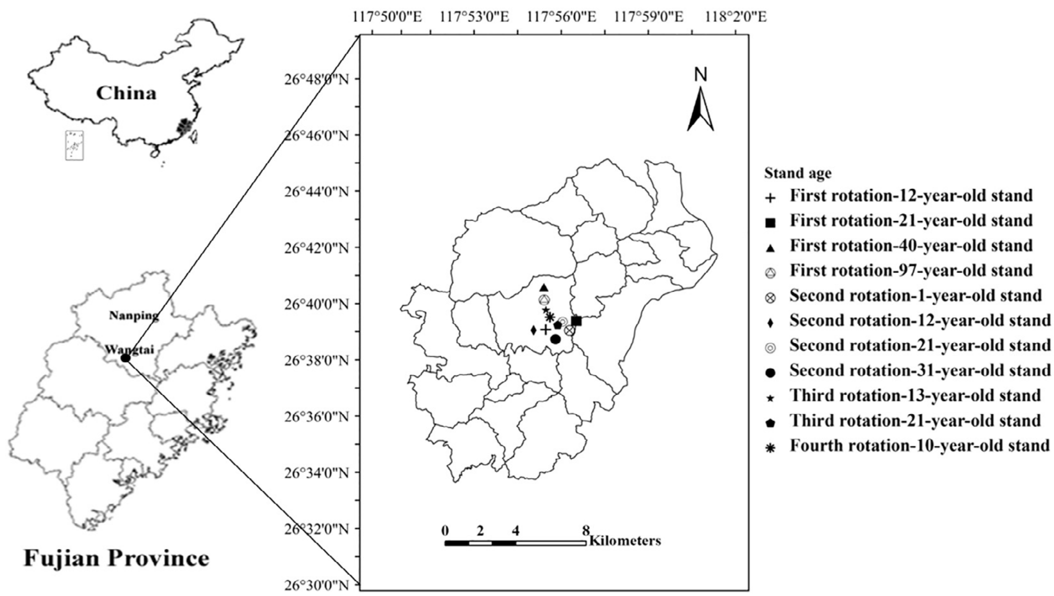

Fig. 1. Location map of the study area.

Worldwide, deforestation on a large scale continues to be carried out for commercial timber production, causing significant degradation of soil functions, ecosystem productivity and sustainability; Chinese fir plantations are no exception (Dudley et al., 2014; Wang et al., 2014). While tropical deforestation rates are stabilizing or decreasing in regions such as Brazil, they are increasing in Indonesia, China, and Malaysia, driven by the international demand for wood-derived products, as well as agricultural land for oil palm and rubber plantations (Margono et al., 2014; Abood et al., 2015). Guillaume et al. (2015) observed up to 70% soil organic carbon (SOC) losses in the topsoil in oil palm and rubber plantations in Indonesia compared to rainforest. Kang et al. (2016) evaluated the flow of ecosystem services from Chinese fir plantations in Fujian Province using eight indicators, including soil fertility and carbon storage. These authors concluded that CO_2 fixation dropped considerably after peaking around 5–15 years of plantation age. However, Selvaraj et al. (2017) demonstrated that successive rotations of Chinese fir plantations decreased soil carbon stocks in the early stages, but these recovered after 25 years. Previous studies have demonstrated that conversion of native forests to plantations caused reductions in soil organic carbon and nitrogen stocks (Chen et al., 2013; Marin-Spiotta and Sharma, 2013; Guan et al., 2015; van Straaten et al., 2015), soil nutrient availability, microbial structure, including fungal and bacterial community, and enzyme activity (Yang et al., 2010; Vitali et al., 2016; Wang et al., 2017; Zhang et al., 2017). Thus, it is evident that current management practices in Chinese fir plantations influence soil properties, with a feedback in decline of timber yield and productivity. Therefore, preventing soil degradation and evaluating the effects of increasing management intensity on soil properties are issues of paramount importance, especially in the context of an ever-increasing social awareness of the urgent need for much more sustainable production practices (Garnett et al., 2013).

Most previous studies focused on one or a few soil properties, but it is necessary to identify several appropriate indicators that can be monitored to provide information about soil functions. Despite the close relationship between stand age, rotations, and soil properties, there is insufficient information about the dynamics of soil quality indicators between successive rotations in Chinese fir plantations.

In forestry, soil quality monitoring has been acknowledged as a fundamental aspect of sustainable management (Burger and Kelting, 1999). Soil quality plays an important role in managed plantations by supporting biomass production and carbon sequestration, which are two important functions associated with managed forest ecosystems (Zhou et al., 2015). Many approaches have been used to select soil quality indicators, and develop a soil quality index (SQI), but these are usually applicable only for specific purposes, and indices are usually valid only under specific environmental and management conditions (Brejda et al., 2000; Askari and Holden, 2014). Therefore, indicators should be selected based on their ability to represent soil functions specific to the land use and ecosystem under study. For example, large areas of tropical montane cloud forest in Mexico have been converted into croplands and secondary forest of different ages through slash-and-burn techniques. Soil organic carbon, pH, plant-available P, organic horizon thickness, and exchangeable Al^{3+} were identified as soil quality indicators to study forest recovery in this ecosystem (Bautista-Cruz et al., 2012). Despite the emphasis on this issue in early studies (Burger and Kelting, 1999; Knoepp et al., 2000; Page-Dumroese et al., 2000; Schoenholtz et al., 2000), only minimal attempts have been made to identify soil quality indicators for sustainable plantation management.

Previous studies have assessed changes in soil properties (physicochemical and biological), and carbon stock, but not comprehensive soil quality over rotation periods and stand age of Chinese fir plantations (Zhang et al., 2004; Jian et al., 2009; Chen et al., 2013). Many indices have been developed to gain expert knowledge on changes in soil quality due to time (inherent) and management practices (dynamic), particularly in agricultural and horticultural sectors (Liebig et al., 2004; Armenise et al., 2013). However, soil quality changes in Chinese fir ecosystems are not well understood. Moreover, earlier evaluations of soil quality were carried out at the surface level (Tesfahunegn et al., 2011; Raiesi and Kabiri, 2016; Seker et al., 2017), which provided incomplete information, since soil functions are also driven by pedogenic processes (Vasu et al., 2016).

In this study, we aimed to fill in this gap in our knowledge by studying soil quality in Chinese fir plantations of four different ages and rotation cycles in Fujian Province, China. The specific objectives of the study were: i) selection of soil properties for preparing a minimum data set (MDS) for soil quality evaluation in Chinese fir plantations, ii) calculation of SQI using the weighted index method, and iii) identification of indicators for soil quality monitoring and their relative contribution to soil quality.