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# Soil labile organic carbon and carbon-cycle enzyme activities under different thinning intensities in Chinese fir plantations

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ABSTRACT

Thinning is a silvicultural tool that is used to facilitate the growth of timber plantations worldwide. Plantations are important $CO_2$ sinks, but the mechanism by which thinning affects the quantity and stability of soil organic carbon (SOC) is poorly understood. In this study, we examined the effects of different thinning intensities (low-intensity thinning treatment with 30% of the trees removed; high-intensity thinning treatment with 70% of the trees removed; control treatment without tree removal) on the quantity and stability of SOC in Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook) plantations in southeastern China. The amounts of SOC, microbial biomass carbon (MBC), easily oxidizable carbon (EOC), cold-water- soluble organic carbon (CWSOC) and hot-water- extractable organic carbon (HWEOC) and the carbon-cycle-related enzyme activities (β-glucosidase, invertase and cellulose) were quantified. We found that thinning significantly decreased the amount of SOC compared with the control treatment, but the effect differed by sampling date. The MBC and EOC were significantly higher in the high-intensity thinning treatment than in the control and low-intensity thinning treatments, whereas the invertase and β-glucosidase activities were significantly higher in the control treatment. However, the amounts of CWSOC, HWEOC and cellulose activity did not differ among the treatments, which indicates that the MBC, EOC and the activities of invertase and β-glucosidase were better indicators of changes in SOC to thinning. In addition, the MBC, EOC, CWSOC and the β-glucosidase and cellulase activities peaked in the warmer months. Our results indicate that thinning treatments in Chinese fir plantations decreased the SOC quantity and enzyme activities and that high-intensity thinning may lead to an increase of labile SOC.


## 1. Introduction

Global forests store approximately 861 Pg of carbon (C), which represents nearly 44% of the carbon that is stored in the soil, and as a major C sink, even small impacts of the management of forest soils can strongly influence the global C cycle (Dixon et al., 1994; Pan et al., 2011). A major focus in forest management is to promote the increase of this sink (Jandl et al., 2007; Achat et al., 2015; Moreno-Fernandez et al., 2015). Soil organic carbon (SOC) can be divided into labile and recalcitrant fractions based on the mean residence times in the soil. Land management practices tend to have little influence on recalcitrant C because of its longer turnover time (Haynes, 2005). In contrast, labile SOC fractions, which have mean residence times that range from years to several decades, can respond rapidly to forest management and can be used as a sensitive indicator of changes in SOC because they are the main source of C that is released from soil to the atmosphere and have a potential to accelerate the decomposition of recalcitrant carbon by a priming effect through soil microorganisms and thus break soil carbon stability (Mao et al., 2012; Qiao et al., 2014; Shang et al., 2016). In addition, the activities of soil carbon cycle-related enzymes (e.g., β-glucosidase, invertase and cellulase) control the decomposition of organic carbon and reflect the metabolic

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requirements of the soil microbial community and the status of the available carbon resources; thus, these enzyme activities can aid in understanding the variations in SOC in response to forest management (Guan et al., 2014; Veres et al., 2015).

Thinning is an important forest management practice in both natural forests and plantations worldwide. This technique may increase forest nutrient availability, productivity and biodiversity, and it is an important tool for manipulating species composition (Verschuyl et al., 2011). Tree removal and the subsequent opening of the forest canopy by thinning change the microclimatic characteristics of the soil and affect the quantity and quality of potential organic inputs and the leaching of dissolved organic matter, thereby modulating SOC (Barg and Edmonds, 1999; Wic Baena et al., 2013). Thinning commonly decreases SOC by reducing litter inputs into the soil and possibly through the microclimate-driven acceleration of decomposition rates (Piene and Cleve, 1978; Covington, 1981; Jandl et al., 2007). However, long-term thinning practices have been reported to increase soil carbon by enhancing root system decomposition in thinned trees and understory growth after canopy removal (Selig et al., 2008). Despite an abundance of studies about the effects of thinning on the total SOC of the forest floor, few have examined how thinning influences labile carbon pools and carbon cycle-related enzymes in the mineral soil (Chiang et al., 2010; Geng et al., 2012; Chen et al., 2015), and the results are still controversial. For example, Bolat (2014) and Yuan et al. (2010) found thinning increased labile organic carbon, but decreases have been reported in other studies (Schilling et al., 1999; Hassett and Zak, 2005). In addition, because seasonal variations in soil temperature and aboveground vegetation might affect the ability or strategy of microbial decomposers to efficiently use SOC, the thinning effect on labile SOC and enzymatic activities may vary seasonally (Balser and Wixon, 2009; Liptzin and Silver, 2009; Keiblinger et al., 2010; Zhou et al., 2012).

Chinese fir (*Cunninghamia lanceolata* [Lamb.] Hook) is an important fast-growing, evergreen coniferous timber species that has been widely planted in southeastern China for more than 1000 years (Chen, 2003). Because of its high commercial value, Chinese fir plantations, which are typically high-density monocultures, have been widely established in previous natural broadleaf forests, and short rotation forestry has become common over the past century in an attempt to meet the rising demand for timber (Tian et al., 2011). These Chinese fir monoculture plantations are carbon sinks, but they are more susceptible to fires and pests than the forests that they have replaced. Furthermore, soil nutrient depletion and yield reduction become common problems after one or more rotations (Tian et al., 2011). Thus, silvicultural practices that recreate historic forest stand structures and thereby optimize the use of the soil, have been a focus of the sustainable management of Chinese fir plantations in recent years, particularly in terms of maintaining soil productivity and ecosystem sustainability.

This study aims to assess the response of SOC, its labile components and related enzyme activities to different thinning intensities. We investigated how the concentrations of SOC, microbial biomass carbon (MBC), easily oxidizable carbon (EOC), hot water-extractable organic carbon (HWEOC) and cold water-soluble organic carbon (CWSOC) as well as the activities of β-glucosidase, invertase and cellulase change following thinning. The specific objective was to assess (1) how different thinning intensities (0%, 30% and 70% stem-only thinning) influence these soil labile SOC fractions and carbon cycle-related enzyme activities and (2) whether the effects of thinning vary with the season. We hypothesized that with increasing thinning intensity, 1) the SOC and labile components will decrease because of the lower carbon inputs from trees after partial canopy removal; 2) the C-cycle enzyme activities will increase because the microclimate and light environment increase the SOC decomposition rate; and 3) the labile components and related enzyme activities peak in the summer months because of their high sensitivities to temperature and precipitation.

## 2. Materials and methods

### *2.1. Study area and thinning experiment*

The study was conducted on a 26-year-old Chinese fir plantation at the Lishui Tree Farm Research Station (119°01′E, 31°36′N) of Nanjing Forestry University in Jiangsu, China. The site is located at an elevation of 100 m and has a slope of 15° with a southern orientation. The soil is a Haplic Luvisol (FAO, 1998) and is generally no more than 30 cm deep. The climate of the study area is subtropical with a mean annual temperature of 15.5 °C, a mean annual sunshine duration of 2146 h, a mean annual precipitation of 1005.7 mm, and a mean frost-free period of 220 days per year from 1995 to 2014. The monthly temperature and rainfall both peak in the summer months May–October (Supplementary Fig. S1).

Nine experimental plots (20 × 20 m) were established under an overstory that was dominated by Chinese fir in a completely randomized design with three replicates for each of the three treatments: no thinning (CK, control), low-intensity thinning (LIT, 30% of the trees removed) and high-intensity thinning (HIT, 70% of the trees removed). To reduce potential edge effects, each plot was surrounded by a 5 m-wide buffer zone. Whole-tree thinning was performed from February to April 2006. The trees in the thinning treatments were thinned from below (i.e., the subcanopy/suppressed trees were removed), and the distribution of the remaining trees was evened. All of the thinned stems were removed from the plots and used as commercial wood. The stand characteristics in the different treatments, including the plant species composition, mean tree height, diameter at breast height (DBH), stand density and biomass, were measured in October 2012 (Table 1). The fine root biomass was measured (Dong Wang and Xinli Chen, unpublished data) using 10 soil cores (5 cm diameter × 20 cm deep) that were collected from the site during the first weeks of January, March, May, July, September and November 2013. The fine roots were sorted into diameter ≤ 2 mm, dried at 85 °C for 48 h and weighed (Table 1).

### *2.2. Soil sampling*

In each of the nine experimental plots, soil samples were taken at two mineral soil depths (S1, 0–10 cm; S2, 10–25 cm) using a 4.0-cm auger in the fall (October 3, 2012), winter (January 3, 2013), spring (April 3, 2013), and summer (July 3, 2013). Three sampling points were selected at random locations within each plot. The soil samples from different sites were pooled and mixed thoroughly, sieved (2-mm mesh), and visible roots and insects were removed. Each pooled soil sample was divided into two parts; one part was stored at 4 °C for the analysis of MBC, HWEOC, and CWSOC concentrations and soil β-glucosidase activity within 3 days, and the remaining part was air-dried to measure the SOC and EOC concentrations and both invertase and cellulose, whose activities can be maintained in air-dried at room temperature for 1 month (Schinner and Vonmersi, 1990). Soil temperatures at depths of 10 cm and 20 cm were recorded with temperature sensors (DS1921G-F5#, Maxim, USA) every 30 min from September 15, 2012 to July 3, 2013.

### *2.3. Chemical and biochemical analyses*

The soil pH was determined using a glass electrode with a soil: solution ratio of 1:2.5. The moisture content was determined by oven drying the samples at 105 °C. The SOC was measured by wet