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# Positive interactions between *Pinus massoniana* and *Castanopsis hystrix* species in the uneven-aged mixed plantations can produce more ecosystem carbon in subtropical China

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ABSTRACT

Silvicultural practices are an important determinant of tree growth and stand structure. However, the potential advantages of long-term forest management, i.e., mixing valuable non-$N_2$-fixing broadleaf tree species, such as *Castanopsis hystrix* Miq., with Masson pine (*Pinus massoniana* Lamb.) to increase stand growth and ecosystem carbon storage, remain poorly understood. In this study, we assessed tree growth, aboveground carbon accumulation, and belowground carbon sequestration in 26-year-old monocultures of *C. hystrix* ($^{100}C_{26}$), 26-year-old monocultures of *P. massoniana* ($^{100}P_{26}$), 50-year-old monocultures of *P. massoniana* ($^{100}P_{50}$), and even- and uneven-aged ($^{50}C_{26}$ + $^{50}P_{26}$ and $^{50}C_{26}$ + $^{50}P_{50}$, respectively) mixed plantations. Carbon storage within the total ecosystem and in the tree and soil layers of $^{50}C_{26}$ + $^{50}P_{50}$ mixed plantations was significantly greater than values predicted based on the means of the $^{100}C_{26}$ and $^{100}P_{50}$ monoculture plantations ($p < 0.05$). By contrast, differences within the shrub and litter layers were not significant, nor were the differences between observed and expected carbon storage values in the total ecosystem, except in the case of carbon stock in $^{50}C_{26}$ + $^{50}P_{26}$ mixed plantation soils. These results indicate that plantations of uneven-aged mixtures of *P. massoniana* and *C. hystrix* promote carbon sequestration via positive interactions.

## 1. Introduction

Conventional forest management in China over the past several decades has primarily been based on the large-scale and continuous development of monocultures of broadleaf and coniferous species. However, this approach has contributed to serious ecological problems, including soil erosion, decreases in soil nutrient content, and reduced biodiversity (He et al., 2013; Wang et al., 2013). With recent policy-guided demand for higher production levels, economic viability, and ecological services, including carbon sequestration, there has been a shift to the cultivation of mixed plantations of economically and ecologically valuable species (Piotto et al., 2010; Hvistendahl, 2012; Puettmann et al., 2015). Studies in temperate and tropical regions have shown that mixed-species plantations can improve carbon sequestration by soil or biomass (Parrotta, 1999; Resh et al., 2002; Wang et al., 2009; Forrester et al., 2013; Huang et al., 2014). Ewel et al. (2015) found that a steeply increasing growth differential between mixed stands and monocultures may account for the inferred complementarity. Other studies have shown that broadleaf tree species mixing with coniferous tree species (1) promotes the growth of the planted trees and increases overall stand productivity compared with pure stands (Binkley, 2003; Nord-Larsen and Meilby, 2016) via improving capture, supply, or resource use efficiency (i.e. light, nutrient and water) (Kelty, 2006; Pretzsch et al., 2015; Chamagne et al., 2017); (2) positively affects litter quantity and quality (Wang et al., 2013); and (3) improves the nutrient balance (Thelin et al., 2002). Although short-term studies in grasslands have clearly shown positive outcomes with mixed stands (Spehn et al., 2000; Nyfeler et al., 2009), there are large differences in the structure

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and physiology between trees and grasses, i.e., within a single year, short-lived grasses can rebuilding the whole canopy. In contrast, trees take much longer to develop their crowns and small differences in tree crown architectural properties could accumulate year after year to have much larger effects as the stand canopy develops, and forest ecosystems require a long time and large areas to be treatment experiment (Scherer-Lorenzen et al., 2005). To date, however, the effects on long-term forest management of introducing non-$N_2$-fixing broadleaf tree species into pure coniferous plantations remain largely unclear.

Masson pine (*Pinus massoniana* Lamb.) is one of the two most important coniferous species for timber production, carbon storage, and other ecological services in subtropical China (Zeng et al., 2011). The amount of forest area planted with this species has increased greatly, reaching > 17.39 million hectares and representing 8.92% of the total forest area of China (Kuang et al., 2008; SFA, 2010). The desirable features of this species include its fast growth, high yield, variable light tolerance, and drought resistance. However, pure Masson pine plantations also have lower biodiversity and soil fertility, cause extensive habitat loss and soil erosion, and thus increase the vulnerability of these forests to pests and diseases, ultimately compromising ecosystem functions. To address the sustainability requirement of forest management, even- or uneven-aged mixed broadleaf and coniferous tree species plantations are currently preferred. *Castanopsis hystrix* Miq. is a large evergreen member of the Fagaceae family and a valuable indigenous tree species in the evergreen broadleaf forests of subtropical China (He et al., 2013). Although combining *P. massoniana* and *C. hystrix* in mixed-species plantations could increase site productivity (He et al., 2013), the impact of this forest management strategy on carbon sequestration within the ecosystem is poorly understood.

Belowground carbon storage is the largest carbon pool in forest ecosystems, second only to aboveground biomass (Sharma et al., 2010; Chen et al., 2012). Protecting and enhancing soil carbon stock is a global challenge. Silvicultural practices can have marked effects on soil carbon stock (Wang et al., 2013) and the soil carbon cycle because tree species and forest stand structures alter light, temperature, and moisture patterns as well as the input of organic material. Forest management is a strong determinant of these processes, with large changes resulting from a shift from pure to mixed plantations. Most studies have shown that aboveground organic matter and carbon storage increase in mixed-species plantations; however, their impact on soil carbon stock is controversial. Some studies have shown that soil carbon stock is increased in mixed-species plantations because of an increase in organic matter input (aboveground and roots) (Yang et al., 2003, Zhang et al., 2012); however, others have observed few effects or even decreases (Raich et al., 2006; Wang et al., 2009). These inconsistent findings suggest that soil carbon storage reflects the inputs of plant litter and other organic detritus and that organic matter decomposition is controlled by biotic (tree traits and soil microbial communities) and abiotic (soil chemical and physical properties) factors (You et al., 2014, 2016). Thus, despite a much improved understanding of the effects of mixed-species plantations on soil carbon stock, little is known about the effects of management practices based on mixed-species plantations.

In this study, we designed a long-term coniferous plantation modification project (CPMP) in a southern subtropical region of China (Pingxiang, Guangxi Zhuang Autonomous Region) based on a multipurpose forest. The project was initiated in 1983, and the forest was a mixture of *C. hystrix* and *P. massoniana*. The main objectives of the CPMP were to examine the impacts of three management strategies (monoculture, even-aged mixture, and uneven-aged mixture) on multiple taxa, environmental variables, and layered and multipurpose forests, and therefore on ecosystem functions and processes (Cai et al., 2007). Specifically, we investigated whether the introduction of valuable broadleaf tree species (non-$N_2$-fixing species) into Masson pine plantations would increase stand growth and ecosystem carbon storage during long-term forest management. The results contribute to the establishment of best practices in the field of silviculture.

## 2. Materials and methods

### 2.1. Site description and experimental design

The study site was located at the Experimental Center of Tropical Forestry (ECTF; 22 °02′–22 °04′N, 106 °51′–106 °53′E), Chinese Academy of Forestry, Pingxiang, Guangxi Zhuang Autonomous Region, China. The topography of this region largely consists of low mountains; elevations range from 430 m to 680 m. The soils are mainly lateritic, and the climate is characterized by hot, humid summers and mild winters. The mean annual temperature is 21 °C, with a daily mean of > 30 °C for approximately 4 months of the year. The mean annual rainfall is approximately 1400 mm, with the bulk falling during the 180-day monsoon period from April to September. Mean annual evaporation is approximately 1300 mm, and relative humidity is 82% (Huang et al., 2014).

Five planted forests were established in 1983 to assess above- and belowground carbon sequestration, tree characteristics, and competition. These sites consist of a 33 ha monoculture of 26-year-old *P. massoniana* ($^{100}P_{26}$); an 18 ha monoculture of ca. 50-year-old *P. massoniana* ($^{100}P_{50}$); a 33 ha monoculture of ca. 26-year-old *C. hystrix* ($^{100}C_{26}$); an 18 ha even-aged mixture (50:50) of *C. hystrix* and *P. massoniana*, each ca. 26 years of age ($^{50}C_{26} + {}^{50}P_{26}$); and an 18 ha uneven-aged mixture (50:50) of ca. 26-year-old *C. hystrix* and ca. 50-year-old *P. massoniana* ($^{50}C_{26} + {}^{50}P_{50}$). Stands of $^{100}P_{26}$, $^{100}C_{26}$, and $^{50}C_{26} + {}^{50}P_{26}$ were established in the spring of 1983 with 1-year-old container seedlings at an initial planting density of 2500 trees $ha^{-1}$ after 24-year-old *P. massoniana* plantations had been felled. Stands of $^{50}C_{26} + {}^{50}P_{50}$ were established such that *C. hystrix* (1-year-old container seedlings) was interplanted into preexisting 24-year-old stands of *P. massoniana* in 1983, with a spacing of 2500 trees $ha^{-1}$. The proportion in the mixed plantation stands was 1:1. Prior to the establishment of the current plantations, the area was covered by a planted *P. massoniana* forest that had been established in 1959 on a historically evergreen monsoon forest (Cai et al., 2007). All forest types experienced similar stand management regimes during the experimental period.

The study site lies on 14–17° hill slope, 3 km in length, oriented southeast–northwest. A 150 m buffer separates the five plantation types. In 2009, 26 years after the initial establishment of the plantations, six sampling plots (20 m × 20 m) were randomly established within each of the five plantation types, with variation in management history, topography, and spatial representation taken into account. The six sampling plots within a single experimental stand were well separated, with distances of at least 200 m between adjacent plots.

### 2.2. Tree biomass measurements

In each plot, the diameter at breast height (DBH; 1.3 m) and the height of all trees in each plot were measured. Seven trees were selected within each plantation type based on diameter and tree height classes. After a selected tree was felled, its total height was measured with a steel measuring tape (accuracy: 0.01 m). The aboveground biomass (AGB) of the trees was divided into 2 m sections and measured according to Monsic's stratified clip method. Each bole was separated into stem, bark, branches, and leaves, and their fresh weights were determined. The belowground biomass (BGB) of the sampled trees was dug out and examined using the open-cut method. Because much of the root growth was shallow and lateral, it was difficult to distinguish the fine roots of one tree from those of another. To address this problem, we excavated large soil pits (diameter: 2.0 m, depth: 1.0 m) around each target tree. The size of these pits was chosen under the assumption that foreign fine roots collected within the pit would be balanced by intrinsic fine roots left in the soil. The fresh weights of the stump roots, thick roots (diameter > 2.0 cm), medium-thick roots (0.5–2.0 cm), and