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Reforestation makes a minor contribution to soil carbon accumulation in the short term: Evidence from four subtropical plantations

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ABSTRACT

Reforestation increases substantial carbon stock in plant biomass. However, reforestation's effect on soil carbon accumulation remains unclear, which hampers our understanding of carbon cycling in forest ecosystems. The change patterns of soil carbon storage in four young plantations, *Eucalyptus urophylla* monoculture (EU), *Acacia crassicarpa* monoculture (AC), *Castanopsis hystrix* monoculture (CH), a mixed plantation of 10 native tree species (MX), and a naturally recovered shrubland (NS), were compared at five stand ages during development in subtropical China. We observed that plant biomass was higher in plantations with fast-growing species (i.e. EU and AC) than with slow-growing species (i.e. CH and MX). However, no significant differences in soil carbon storage were observed among the four plantations with the same stand ages. Meanwhile, there were no significant differences in soil carbon storage among the four plantations and NS. Furthermore, soil carbon storage exhibited a similar change pattern for the four plantations and naturally recovered shrubland during the 10-year period of early vegetation development. Specifically, soil carbon storage decreased slightly and non-significantly during the first 4 years (from 23.84 Mg ha^{-1} to 20.79 Mg ha^{-1}) and increased thereafter (35.85 Mg ha^{-1} in 10-year-old plantations). These results suggest that plant biomass increment and soil carbon accumulation were unsynchronized, and early reforestation had no significant effect on soil carbon accumulation. We conclude that plantations did not accelerate carbon sequestration in soils at early developmental stages compared with natural recovery and plant biomass may not be an appropriate index for evaluating soil carbon sequestration in young plantation.

1. Introduction

Over the last several centuries, intensified anthropogenic activities have resulted in an increase of atmospheric CO_2 concentration to over 400 ppm (Dlugokencky and Tans, 2016). The rise of CO_2-concentration has caused serious ecological consequences of changes in ecosystem structures and functions (Curtis et al., 1995; Norby and Luo, 2004). Reforestation as a means of carbon sequestration plays a crucial role in alleviating CO_2-concentration increase (Hunter, 2001). The average annual increment of the world plantation area was approximately 3.60×10^6 ha from 1990 to 2010. The increase in plantation area in China is most remarkable in the world (FAO, 2010). China has a total plantation of approximately 6.9×10^7 ha, which is about one third of the world's total plantation area (State Forestry Administration, 2014). Plantations are responsible for approximately 80% of the carbon sink increment in China (Fang et al., 2007) of which plantations in southern China have contributed to more than 65% of the national carbon sinks (Piao et al., 2009). However, there is little information on the contribution of reforestation to carbon sequestration in soils.

Soil carbon is primarily derived from plants (Kuzyakov and Domanski, 2000). Greater plant biomass could facilitate the inputs of plant-derived C (Bekku et al., 1997; De Deyn et al., 2008). Therefore, plant growth may promote carbon sequestration in soils. The variation of soil carbon can be partially explained by plant biomass indices such as DBH and H (Ren et al., 2013). However, it is still unclear how the soil carbon pool changes with plant growth in young plantations.

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Numerous studies have reported that soil carbon storage is related to forest age, root turnover, litter quality and soil chemical properties (Bashkin and Binkley, 1998; He et al., 2013). Plantation types markedly affect carbon accumulation in vegetation and soils (Zheng et al., 2008; Snell et al., 2016). The effect of plantation types on soil carbon accumulation could primarily depend on litterfall quality and soil nutrient status (Binkley and Binkley, 1998; Wang et al., 2013). Litterfall quality is controlled by tree species of reforestation (Polyakova and Billor, 2007). Soil nutrient availability influences soil carbon dynamics through plant-soil-microbial interactions (Bohlen et al., 2001; Moore et al., 2015). High soil N availability stimulates tree growth, which potentially increases carbon inputs into soils through litterfall and rhizodeposition, and promotes carbon sequestration in soils by decreasing decomposition rates of old litter and recalcitrant soil organic matter by suppression of soil microbes and chemical stabilization (Liljeroth et al., 1994; Jandl et al., 2007). Moreover, previous studies suggest that low soil fertility limits soil carbon sequestration (van Groenigen et al., 2006; Hoogmoed et al., 2014). However, these results were obtained through comparisons of paired sites performed only one time or through chronosequence study of only one plantation type; such a small sample is insufficient for supporting these researchers' conclusions. Meanwhile, Marín-Spiotta and Sharma (2013) synthesized 81 studies in tropical locations. They found that soil carbon in tropical successional plantation forests was not significantly affected by vegetation type and that climate factors drove greater variability in soil carbon levels than forest age. The impact of reforestation on soil carbon, which is important for understanding carbon cycling in forest ecosystems (Huntington, 1995; van Straaten et al., 2015), is still debatable.

The main objectives of this study were to (1) understand how soil carbon changes with plant growth, and (2) assess the effects of reforestation on soil carbon storage in young subtropical plantations. We used inventory data from the Heshan National Field Research Station of Forest Ecosystem to estimate plant biomass and soil carbon storage in four plantations and a naturally recovered shrubland in the early developmental stages of vegetation.

2. Materials and methods

2.1. Study area

This study was conducted at the Heshan National Field Research Station of Forest Ecosystem (112°50′E, 22°34′N), Guangdong Province, China. The climate in this region is typical subtropical monsoon with a distinct wet (April to September) and dry season (October to March). The mean annual precipitation is 1688 mm and mean annual temperature is 22.3 °C from 2005 to 2012. The soil is classified as Ultisol developed from sandstone. The previous vegetation type was a degraded *Pinus Massoniana* plantation, probably observed due to intensive land use. Plots in naturally recovered shrubland and four plantations, which were the study sites of our research, were established in 2005 on hilly land with similar site characteristics (Chen et al., 2015). Each plantation type had three replicated plots. Each plot had an area of 1 ha and was randomly distributed in this experimental area that had a total area of 50 ha. Trees were planted with a spacing of 2 m × 3 m (approximately 1650 trees per hectare) in the four plantations. The four plantations in this study were *Eucalyptus urophylla* monoculture (EU), *Acacia crassicarpa* monoculture (AC), *Castanopsis hystrix* monoculture (CH), and mixed plantation of 10 native tree species (MX). Meanwhile, a naturally recovered shrubland (NS), where no trees were planted, was considered as the control. The mixed plantation had 10 native tree species, *Castanopsis hystrix*, *Liquidambar formosana*, *Magnoliaceae glance*, *Machilus chinensis*, *Cinnamomum burmanii*, *Tsoongiodendron odorum*, *Jacaranda acutifolia*, *Bischofia javanica*, *Schima superba*, and *Dillenia indica*. Understory vegetation in this region is highly dominated by the fern, *Diranopteris dichotoma*, and other common herbaceous plants included as *Blechnum orientale* and *Miscanthus sinensis*, shrubs as *Rhodomyrtus tomentosa*, *Melastoma candidum*, *Gardenia jasminoides*, and *Ilex asprella var. asprella*.

2.2. Inventory of plant biomass

In 2005, a permanent quadrat plot of 900 m^2 (30 m × 30 m) was established in each of the three replications for each plantation and NS. Vegetation inventories were conducted in 2006, 2008, 2009 and 2011 in plots that were 1, 3, 4 and 6 years old, respectively. The height (H) and DBH (diameter at breast height for trees, basal diameter for shrubs) of all trees and shrubs were measured for each inventory. Each plant with a DBH of more than 1 cm was marked and numbered in 2011. The allometric equations based on the DBH and H were applied to calculate biomass for trees and shrubs in each plantation (Chen et al., 2015).

Measurement of herb biomass was carried out after 6 years. In order to avoid destroying the permanent quadrats, we selected three typical 1 m × 1 m subplots just around the quadrat and harvested all above-ground and below-ground biomass of herbs. All samples were taken to the laboratory and oven-dried at 65 °C to obtain constant weight for biomass estimation.

Litter mass was collected in 1 m × 1 m baskets constructed of plastic screening with 1 mm mesh. Three baskets were used for litter mass collection for each quadrat. Litter mass was collected monthly from September 2009 to August 2012 for all plantations. Litter mass for naturally recovered shrubland was not collected because very little litter was produced by the dominant fern, *Diranopteris dichotomy*.

Fine roots were harvested by using a soil sampler with 3.0-cm diameter in September 2013. Fine root biomass were sampled from nine sampling points at a 0–10-cm layer to yield one pooled sample for each quadrat. Hence, three replicate fine root biomass composite samples were collected for each plantation. All fine root (<2 mm) samples were taken back to the laboratory and washed and were subsequently oven-dried at 65 °C to obtain constant weights for biomass estimation.

2.3. Soil sampling and analysis

Surface soil samples were collected in five stand ages, corresponding to 0 (in 2005, after the tree planting), 4, 6, 7 and 10 years old. The soils were sampled with a corer (3.0 cm in diameter) at 0–20-cm depths from nine randomly selected microsites in each quadrat. Three cores of the same depth from the same slope position were combined to yield one pooled sample, and three pooled samples were collected for each quadrat. Visible plant residues and roots were removed by hand. Then, the soil sample was sieved using a 2 mm bore diameter and taken back for physicochemical properties analysis. Soil organic carbon was determined by using the traditional potassium dichromate oxidation method (Lu, 1999). Soil carbon storage at a specific depth in a given area was calculated as

$$SOCs = C \times T \times BD \times (1 - F)/10$$

where SOCs is the soil organic carbon storage (Mg ha^{-1}), C is the soil organic carbon concentration (g kg^{-1}), T is the thickness of soil horizon (cm), BD is the bulk density (g cm^{-3}), and F is the mass percentage of fragments, sand and stone (>2 mm). Soil bulk density for soil samples from both the 0–10-cm and 10–20-cm layers was determined using a steel ring sampler of 100-cm^3 volume (5-cm diameter and 5.1-cm height). Soil bulk density was calculated by dividing the weight of the dried soil by the volume of soil (Guo