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Biomass and carbon storage of *Eucalyptus* and *Acacia* plantations in the Pearl River Delta, South China

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ABSTRACT

Forest plantations represent an important carbon sink. In the Pearl River Delta (PRD) in Southern China, fast-growing *Eucalyptus* and *Acacia* are favoured plantation species, but little is known regarding their efficiency with respect to biomass production, partitioning and dynamics with stand age, or the contribution made by the understory, litter and coarse woody debris (CWD) to the volume of biomass and fixed carbon. Here, a set of 21 plantations of various ages were monitored for the pattern of biomass accumulation and partitioning. A continuous biomass expansion factor (BEF) method was applied to a set of forest inventory data (FID) over the periods 1989–2003 to estimate biomass accumulation, carbon storage and its pattern of change over time. The accumulation of biomass increased with stand age, reaching, respectively, 207.45 and 189.35 t ha^{-1} in mature *Eucalyptus* and *Acacia* plantations. The contribution of secondary biomass from the understory, litter layer and CWD accounted for, respectively, up to 10.2% and 20.3% of the total biomass in the two types of plantation, highlighting the significance of secondary biomass. At a similar growth stage, the ranking of the contribution to secondary biomass in the *Eucalyptus* plantations was litter > herbaceous plants > shrubs > CWD, while in the *Acacia* plantations, it was litter > CWD > shrubs > herbaceous plants. The *Eucalyptus* and *Acacia* plantations in the PRD accumulated some 2.66–7.84 Mt of biomass and sequestered 1.33–3.92 Mt of carbon. For both species, the bulk of the plantations (*Eucalyptus* 82.1%, *Acacia* 89.3%) were at the young to middle-aged stage. The *Acacia* plantations generated a higher biomass density than the *Eucalyptus* plantations. Forest management intensification and reforestation programmes, especially targeting *Acacia* or mixed *Eucalyptus*/*Acacia* forests, offer good potential for future carbon sequestration.

1. Introduction

Planted forests (plantations) are seen as a mitigating measure against the predicted rise in atmospheric carbon dioxide concentration, since trees are efficient sequesterers of carbon (Sands et al., 1999; Hunter, 2001; Kurz et al., 2009). A growing forestry research priority, not least in China, is the need to measure the volume of carbon sequestered in plantations (Brown, 2002; Huang et al., 2012). The area of such plantations in China (5.33 Mha) accounts for 30% of the nation's forested area, and 29% of the global plantation area (FAO, 2007). Most of these plantations are still immature, and so retain a substantial capacity for carbon sequestration (Pregitzer and Euskirchen, 2004; Zhao and Zhou, 2005; Kauppi et al., 2006; Xu et al., 2010). Southern China accounts for >65% of the national carbon sink (Piao et al., 2009), but in the Pearl River Delta (PRD), coverage by evergreen broadleaf primary forest is currently <1.5% of the forested area (Wen and Huang, 2006). In the 1980s, therefore, the provincial Guangdong government instigated a reforestation programme featuring mainly *Eucalyptus* and *Acacia* spp., and targeting areas where the soils had become badly degraded. This effort has succeeded in raising the area occupied by forest in Guangdong province from 26.2% in 1979 to 50.1% in 1998 and 57.0% in 2010, while the 2010 figure for the PRD is 49.5%. The local success of a number of *Eucalyptus* (*Eucalyptus urophylla*, *Eucalyptus citriodora*, *Eucalyptus exserta*, *Eucalyptus tereticornis* and *Eucalyptus camaldulensis*) as well as *Acacia* (*Acacia mangium*, *Acacia auriculaeformis* and *Acacia confusa*) spp. reflects their tolerance of poor soils and their rapid growth rate (Yang et al., 2009a; Chen et al., 2011).

Currently, the dominant tree species used in PRD plantations are *Eucalyptus* and *Acacia*, but neither the means to assess their capacity to sequester biomass and carbon, nor a proper understanding of how this biomass and carbon storage is influenced by the age structure of the plantation, are currently available. The greatest potential for above-ground biomass and carbon storage

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in the forest ecosystem resides in the canopy tree layer, although the understory, litter and coarse woody debris (CWD) can also make a considerable contribution (Peichl and Arain, 2006; Zhou et al., 2008). Ignoring these secondary biomass components probably results in a serious underestimation of total carbon storage, particularly in subtropical forests. Monitoring of the accumulation of biomass by the canopy tree layer over the growth cycle of both *Eucalyptus* and *Acacia* plantations has demonstrated how it increases with stand age (Singh and Toky, 1995; Shanmughavel and Francis, 2001; Bauhus et al., 2004; Zewdie et al., 2009). Nevertheless, *Eucalyptus* and *Acacia* plantations are typically logged within 10 years, as the timber is predominantly destined for pulpwood production (Inagaki et al., 2010). As a result, there is a lack of long term characterization of biomass accumulation or carbon fixation in such plantations. Efforts have been made to study the dynamics of secondary biomass components accumulation by targeting the CWD (Woldendorp and Keenan, 2005), the understory and litter in Mediterranean and tropical *Eucalyptus* forests (Carneiro et al., 2007; Turner and Lambert, 2008), litter in Mediterranean *Eucalyptus* forests (Inagaki et al., 2010), and litter in tropical *Acacia* forests (Inagaki et al., 2010). However, the long-term relative contribution of secondary biomass accumulation to *Eucalyptus* and *Acacia* plantations ecosystem still remains unclear.

The continuous biomass expansion factor (BEF) method is widely recommended as a means of estimating forest biomass and carbon storage at the regional or national level (Brown and Lugo, 1984; Brown and Lugo, 1992; Brown, 2002; Guo et al., 2010). As BEF is calculated as the ratio between total stand biomass and growing stock volume, it has to be based on direct field measurements (Brown et al., 1989; Fang et al., 2001). It has been employed by the commercial forestry sector and by various government agencies to obtain estimates of biomass or carbon storage based on the forest inventory data (FID) (Jenkins et al., 2001; Fang et al., 2005; Wang et al., 2011). A BEF-based estimate of *Eucalyptus* biomass at the national (China) level has been provided by Fang et al. (2001), but as yet there has been no equivalent effort made for *Acacia* plantations.

The current paper focuses on the production, partitioning and dynamics of *Eucalyptus* and *Acacia* biomass with age at both the stand and the regional level. Achieving this required the modification of the BEF approach adopted by Fang et al. (2001) for *Eucalyptus*, and its extension to cover *Acacia*. Our objectives were to test the hypotheses: (1) *Eucalyptus* and *Acacia* plantations of various ages have a high capacity to sequester biomass and carbon; and (2) the secondary biomass in the form of the understory, litter and coarse woody debris make a significant contribution to the overall biomass of these plantations. We also set out to adapt the continuous BEF method to suit a regional scale analysis.

2. Materials and methods

2.1. The experimental site in the PRD

The PRD (21°31′–23°10′ N, 112°45′–113°50′ E) is part of Guangdong Province (Southern China). Its soils are mainly lateritic, and its climate characterized by hot, humid summers and mild winters. The mean annual temperature is 21 °C, but a daily mean of over 30 °C applies over about one third of the year. The mean annual rainfall is approximately 1600 mm, with the bulk falling during the 150 day monsoonal period from April to August. *E. urophylla* and *A. mangium*, and to a lesser extent also *E. citriodora* and *A. auriculaeformis*, are widely grown PRD timber plantation species (Table 1). The study area consisted of 21 sites (of which 11 were planted exclusively to *Eucalyptus*) located in hilly land close to either Guangzhou, Zhuhai or Heshan. The sites were monitored over November–December 2010 for *Eucalyptus*, and December 2010–January 2011 for *Acacia*. The vegetation composition of the *Acacia* understories was more heterogeneous than the *Eucalyptus* understories, as it included patches of acidophilous grasses and native shrubs. The age of the plantations was obtained through interviews with local residents.

2.2. Biomass measurement

At each site, the biomass of the canopy tree layer within a 30 × 30 m square was estimated. Tree heights above 3 m were obtained using a digital hypsometer, and their diameter at breast height (DBH; 1.3 m ground level) measured with a diameter tape. The allometric equations published by Ye et al. (2008) and Ren et al. (2000) were applied to calculate biomass. The understory biomass was estimated by a destructive sampling of five 2 × 2 m plots, involving both shrubs, ferns and grasses growing within the central 1 m^2 of each plot. Shrubs were separated into stem, branches, leaves and root, and herbaceous material into their above- and below-ground components. The fresh weights of each component were obtained directly, and the respective dry weights calculated by obtaining the moisture content following the oven-drying of a weighed sub-sample at 65 °C until it had reached a constant weight. The litter contribution was obtained from a set of five 1 × 1 m quadrates arranged along the diagonal of the main 30 × 30 m square; it included leaf, fruit, bark and twigs (<10 mm diameter). The fresh weight of each component was obtained on site, and dry weights from oven-dried sub-samples, as above. Based on the recommendations of Wei et al. (1997) and Tang and Zhou (2005), felled dead wood and standing dead trees ⩾2.5 cm in diameter and ⩾1 m in height were included in the CWD sample; their moisture content was obtained from oven-dried sub-samples (as above), while the determination of their volume relied on a water displacement method. The total biomass represented the sum of the canopy tree layer, shrub, understory, litter and CWD biomasses.

2.3. The use of BEF to calculate forest biomass and carbon storage

The BEF conversion factor to link vegetative carbon storage or biomass to forest volume was first calculated on the basis of direct field measurements, following Fang et al. (1998, 2001) equation: BEF = $a + b/v$. In this equation, BEF is the biomass expansion factor, v the stem volume per hectare, and a and b are constants for a specific forest type. Using field biomass and volume data, the constants a and b can be readily estimated by regression analysis. The stand volume (v) was calculated using the volume regression equations suggested by Yang et al. (2009b). Since for a specific forest type, BEF can be regarded as constant when stand volume is large enough, the biomass of the *Eucalyptus* and *Acacia* plantations in the PRD was estimated using the Fang et al. (2001) equation $Y = A \times V \times$ BEF, in which Y represented the forest biomass (t ha^{-1}) and A the forest area (ha). This relationship was combined with FID to predict overall biomass. The calculated biomass was converted into fixed carbon by multiplying by 0.5 (Lieth and Whittaker, 1975; Razakamanarivo et al., 2011).

2.4. The FID in the PRD during 1989–2003

The Province level FID was estimated once every 5 years by the local Forestry Department. For the inventory years 1989–1993, 1994–1998 and 1999–2003, both the area under forest and the volume of timber across the whole PRD region were obtained for both plantation types. Individual plantations were classified as either young, middle-aged or mature.