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Effects of *Eucalyptus* litter and roots on the establishment of native tree species in *Eucalyptus* plantations in South China

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ABSTRACT

Transforming plantation monocultures into sustainable, mixed-species forests that contain native species is an important goal in South China. The establishment of native species in *Eucalyptus* plantations is generally considered difficult, however, because of the potential allelopathic effects of *Eucalyptus*. In this study, a field trial with completely randomized block was conducted to determine the degree to which *Eucalyptus* litter and *Eucalyptus* roots limit the establishment of native trees in *Eucalyptus* plantations. Growth of seedlings of four native tree species (*Schima superba*, *Michelia macclurei*, *Cinnamomum burmannii*, *Cinnamomum camphora*) that were tested was inhibited by *Eucalyptus* roots. Seedling emergence was less sensitive than subsequent seedling growth to inhibition by *Eucalyptus* roots. In contrast, litter enhanced the emergence and growth of seedlings of most of the tested species (*Castanopsis chinensis*, *Elaeocarpus sylvestris*, *S. superba*, *Liquidambar formosana*, *C. burmannii*, and *C. camphora*), suggesting that retaining litter on the forest floor may promote the establishment and growth of native tree species in *Eucalyptus* plantations. We propose the following strategies for establishing native tree species in *Eucalyptus* plantations: (1) direct sowing of the native tree species *C. chinensis*, *Castanea henryi*, *Erythrophleum fordii*, and *C. camphora*; (2) transplanting of *E. sylvestris*, *S. superba*, and *Tsoongiodendron odorum*, which had low germination rates but high seedling establishment rates; and (3) the exclusion of *Eucalyptus* roots via inter-row trenching to enhance the establishment of *S. superba*, *L. formosana*, *C. burmannii*, and *C. camphora*.

1. Introduction

Native tree species play a central role in conserving biodiversity, mitigating environmental problems, and maintaining ecosystem services in forests (Foroughbakhch et al., 2001; Ren et al., 2007; Wang et al., 2009b; Rodriguez-Loinaz et al., 2013). Unfortunately, many native forests have been destroyed because of the large-scale and continuous planting of fast-growing exotic tree species such as *Acacia* and *Eucalyptus* species, which are characterized by simple structure and artificial regeneration (Guerrero and Bustamante, 2007; Ren et al., 2007; Calviño-Cancela et al., 2012).

Eucalyptus spp. have been introduced and widely planted in many countries throughout the world because of their high productivity, wide adaptability, and rapid economic returns (Turnbull, 1999; Cossalter and Pye-Smith, 2003). China is now the second largest producer of *Eucalyptus* with an area of 3,680,000 ha, and the area of *Eucalyptus* plantations in South China is expected to increase by 200,000 ha annually (Chen et al., 2013a; Wan et al., 2014). Large-scale *Eucalyptus* plantations have greatly changed forest community structure and function and account for most of the decline in native species richness (Gaertner et al., 2011; Baohanta et al., 2012). Consequently, biodiversity reduction, production loss, and soil degradation in fast-growing *Eucalyptus* monocultures have arisen as major problems that threaten the sustainability of managed forests (Wang et al., 2009b; Boelter et al., 2011; Lamarque et al., 2011; Chen et al., 2013b).

Increasing native species recruitment and biodiversity is increasingly recognized as important for the sustainability of forests (Calviño-Cancela et al., 2012). Plantations containing only a few fast-growing woody species provide a rapid return of economic benefits but may have deleterious ecological effects (e.g., biodiversity loss and soil degradation) that should be mitigated by the establishment of mixed-species plantations (da Silva et al., 2011; Calviño-Cancela et al., 2012). Interest in mixed-species plantations has increased in recent years (Manson et al., 2013). Many previous studies have demonstrated that mixed-species plantations can increase the productivity and improve the ecological

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services of tropical and subtropical forests (Richards and Schmidt, 2010; Gonzalez-Munoz et al., 2011; Bouillet et al., 2013; Epron et al., 2013). Moreover, canopy stratification in mixtures enables different species to make use of the varying light intensities that occur in canopy gaps (le Maire et al., 2013), and differences in root architecture and distribution can reduce competition for nutrients and water (Jose et al., 2006; Forrester et al., 2010; Forrester and Smith, 2012; Grant et al., 2012). Therefore, the establishment of sustainable, mixed-species plantations that include native species has become an important topic for forest management and research (Guerrero and Bustamante, 2007; Baohanta et al., 2012).

Because phenolic acids, volatile oils, and other allelopathic chemicals released from the leaves, bark, and roots of *Eucalyptus* can suppress other plants (Martins et al., 2013; Chu et al., 2014; He et al., 2014), few studies have focused on how to establish mixed-species plantations that contain both native tree species and *Eucalyptus* (Duarte et al., 2006; Zhang and Fu, 2009; Chu et al., 2014). Plant root exudates are a major source of allelopathic chemicals, and these organic compounds greatly affect other plant species (Bertin et al., 2003; Haichar et al., 2014). Most reports, however, have focused on the allelopathic effects of litter extracts; the effects of exudates from living roots have been less studied (Bernhard-Reversat, 1999; Malik, 2004; Singh et al., 2005). In addition, studies on the allelopathic effects of *Eucalyptus* have usually been conducted in the laboratory, and information on the effects of *Eucalyptus* on native species under natural conditions is needed (Willis, 1985; Jose et al., 2006).

Seed germination and seedling establishment, which are key stages in the life cycle of native plants, determine whether a native species can successfully recruit within mixtures (Guerrero and Bustamante, 2007; Wang et al., 2009a; Zhang and Fu, 2009). Some studies found that *Eucalyptus* inhibited seed germination and seedling growth of native species but that the effects were species-dependent (Fang et al., 2009; Zhang and Fu, 2009; Chu et al., 2014). Thus, to enhance the recruitment of native species in *Eucalyptus* plantations, forest managers require information about which native species can tolerate the allelopathic effects of *Eucalyptus* during seed germination, seedling emergence, and seedling growth (Manson et al., 2013).

In the present study, we conducted a field experiment in three independent *Eucalyptus* monoculture plantations. The experiment involved 12 native species and litter removal or/and root exclusion using completely randomized block. The objectives were: (1) to determine the effects of *Eucalyptus* litter and roots on the recruitment of native species in *Eucalyptus* plantations; and (2) to develop management practices for the establishment of native species in *Eucalyptus* plantations.

2. Materials and methods

2.1. Site description

This study was conducted at the Heshan Hilly Land Interdisciplinary Experimental Station, the Chinese Academy of Sciences (CAS), Guangdong Province, China. The field station is located at 22°34′N and 112°50′E. The climate of the region is subtropical monsoon with a distinct wet (from April to September) and dry season (from October to March). The mean annual rainfall is 1700 mm, and most rainfall occurs between May and September. The mean annual temperature is 21.7 °C; the maximum mean monthly temperature is 29.2 °C in July, and the minimum mean monthly temperature is 12.6 °C in January. The soil is laterite (FAO, 2006). Soil water content, organic carbon and pH were 21.4 ± 1.5%, 15.4 ± 2.1 g kg^{-1} and 4.13 ± 0.0, respectively.

The experiment was conducted in three separate *Eucalyptus urophylla* plantations, each of which occupied about 1 ha. The *Eucalyptus* seedlings were transplanted with a spacing of 3 × 2 m on homogeneous degraded hilly land in 2005. When the experiment was started (in December 2007, see the next section), the *E. urophylla* trees were 3 years old and had an average height of 11 m and an average diameter at breast height (DBH) of 7.5 cm.

2.2. The plant species

Germination and seedling growth were assessed for 12 native tree species. The major characteristics of these species are listed in Table 1. All 12 are broad-leaved species that are shade-tolerant in the seedling stage. In addition, all are endemic in South China and have high economic value. These native tree species are dominant in some natural broad-leaved forests, and most of them often coexist with other fast-growing tree species (e.g., *Cunninghamia lanceolata* and *Pinus massoniana*) in South China (Feng et al., 2008). *Delonix regia* and *Erythrophleum fordii* are nitrogen-fixing species. *Tsoongiodendron odorum*, *E. fordii*, and *Cinnamomum camphora* are rare and endangered species. The seeds of *D. regia*, *T. odorum*, and *Elaeocarpus sylvestris* were obtained from a seed company in Guangzhou, China, and other seeds were collected in the autumn and winter of 2007 from the monsoon broad-leaved forest in the Dinghushan Natural Reserve, Guangdong. Full, uniform, and healthy seeds were selected by submerging the seeds in tap water in the laboratory; seeds that floated were discarded. The selected seeds were then stored as indicated in Table 1.

The seeds of some native species were treated before they were sown in the field (Deng, 2003). *Castanopsis chinensis* seeds were placed in running tap water for 3–4 days to kill weevils. *D. regia* seeds were placed in hot water (90 °C) for 10 min, and *Cinnamomum burmannii* seeds were placed in hot water (60 °C) for 15 min and then in warm water (40 °C) for 24 h. The dry seeds of *Liquidambar formosana* were placed in water for 10 min. *E. fordii* seeds were treated with a pure sulfuric acid solution and were then rinsed three times with tap water.

2.3. Experimental design

The experiment used a randomized block design with three blocks (one block in each of the three *Eucalyptus* plantations). Each

Table 1
Major characteristics of the 12 native tree species in the experiment.

Plant species	Family	Life form	Seeds were stored
Castanopsis chinensis	Fagaceae	Evergreen, broad-leaved	In moist sand
Castanea henryi	Fagaceae	Evergreen, broad-leaved	In moist sand
Castanopsis fissa	Fagaceae	Evergreen, broad-leaved	In moist sand
Elaeocarpus sylvestris	Elaeocarpaceae	Semi-evergreen, broad-leaved	In moist sand
Erythrophleum fordii	Caesalpiniaceae	Evergreen, broad-leaved	Dry and aerated with gas exchange
Delonix regia	Caesalpiniaceae	Evergreen, broad-leaved	Dry and aerated with gas exchange
Schima superba	Theaceae	Evergreen, broad-leaved	Dry and aerated with gas exchange
Tsoongiodendron odorum	Magnoliaceae	Evergreen, broad-leaved	In dry sand
Michelia macclurei	Magnoliaceae	Evergreen, broad-leaved	In moist sand
Liquidambar formosana	Hamamelidaceae	Deciduous, broad-leaved	Dry and aerated with gas exchange
Cinnamomum burmannii	Lauraceae	Evergreen, broad-leaved	In dry sand
Cinnamomum camphora	Lauraceae	Evergreen, broad-leaved	In moist sand