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Should Exotic Eucalyptus be Planted in Subtropical China: Insights from Understory Plant Diversity in Two Contrasting Eucalyptus Chronosequences

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Abstract Although Eucalyptus is widely planted in South China, whose effects on native biodiversity are unclear. The objective of this study was to quantify the richness and composition of understory plants in two contrasting Eucalyptus chronosequences in South China. One was in Zhangzhou City with plantation age of 2, 4, and 6 years after clear-cutting Chinese fir forests, while the other was in Heshan City with plantation age of 2, 3, and 24 years that reforested on barren lands. Results showed that the richness of understory plants and functional groups was not significantly altered in the Zhangzhou chronosequence, while increased in the 24-year-old plantations, with a significantly larger proportion of woody plants than the younger plantations for the Heshan chronosequence. Moreover, a higher richness of woody plants accompanied by a lower richness of herbaceous species was detected in the Zhangzhou chronosequence compared with the Heshan one. To balance the need for pulp production and plant diversity conservation, we suggest that intercropping approaches between exotic Eucalyptus plantations and native forests should be considered in the fast rotation Eucalyptus plantations. However, Eucalyptus plantations may be used as pioneer species to sustain ecosystem functioning for the degraded lands.

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Introduction

Domestic wood plants in China are no longer able to meet the rapidly increasing demands for pulp production. For instance, in 2010, about 44 % of total pulp consumed in China was from overseas imports (China Paper Association 2010). Eucalyptus, as exotic plant species, has nowadays played an important role in wood industry in China. Due to their characteristics of fast-growing, high productivity, and good adaptability, Eucalyptus has been widely established in China for potential wood production (Stape et al. 2010). By 2010, the total area of Eucalyptus plantations in China was about 3.68 million ha and has now been expanding for the economic benefits (Yang et al. 2011).

Eucalyptus was introduced to China in 1890 and had been widely planted since 1950s. To date, more than two hundred species of Eucalyptus were planted in seventeen provinces across China (Yang et al. 2011). Much attention has been recently attracted on whether functions and processes of native forest ecosystems would be substantially affected by large areas of Eucalyptus plantations (Stone 2009; Gaertner et al. 2011). One main concern is that Eucalyptus plantations could negatively impact the diversity of native plants (Gaertner et al. 2011), thereby driving shifts in ecosystem properties (Wardle and Zackrisson 2005; Yang et al. 2012). For instance, activities such as artificial afforestation with exotic species are causing loss of biodiversity in many ecosystems (Chapin et al. 2000).

Studies have focused on the effects of Eucalyptus plantations on forest ecosystem functions, such as fauna richness (Proença et al. 2010), soil fauna and microbial community composition (Liao and Chen 1990; Cao et al. 2010; Wu et al. 2013), and plant diversity compared to native vegetation types (Wang et al. 2011; Zhang et al. 2014). Nevertheless, little is known about the effects of Eucalyptus plantations with different ages on the diversity of understory plants, which has been considered as an important component for forest ecosystems (Nilsson and Wardle 2005; Wu et al. 2011).

In this study, we investigated the diversity of understory plants in two contrasting Eucalyptus chronosequences. Both chronosequences were the first rotation plantations. Zhangzhou chronosequence was established after clear-cutting of native Chinese fir forests (i.e., 2-, 4-, and 6-year-old plantations) and Heshan chronosequence was launched on a barren hilly land (i.e., 2-, 3- and 24-year-old plantations). Both Zhangzhou and Heshan regions are located in South China, where Eucalyptus is widely planted. We intended to address the following hypotheses: (1) the diversity of understory species would decline in the Zhangzhou (fast rotation) chronosequence but will enhance in the Heshan (long-time regeneration) chronosequence, as they have contrasting land-use history; (2) the characteristics of plant diversity in the two chronosequences would be different due to the initial conditions.

Materials and Methods

Study Sites

Zhangzhou Chronosequence

This chronosequence was located at Tianma National Forestry Farm (117° 28′ E, 24° 37′ N), Zhangzhou City, Fujian Province, China. The climate in this region is subtropical monsoon with mean annual precipitation of 1503 mm and mean annual temperature of 21 °C, and the soil is acrisol. Experimental plantations used in this study were established on the homogenous soil texture after clear-cutting and prescribed burning of original vegetation-Chinese fir forests. Plants were spaced at 3 m × 2 m from each other with *Eucalyptus urophylla* × *Eucalyptus grandis* saplings in 2007, 2009, and 2011, i.e., plantation age of 2, 4, and 6 years, respectively, relative to 2013 when we took measurements. Each sapling was fertilized twice (i.e., at the start of planting and 1 year after planting) with 500 g of organic fertilizer.

Heshan Chronosequence

This chronosequence was chosen from the Heshan National Field Research Station of Forest Ecosystem (112° 50′ E, 22° 34′ N), Heshan City, Guangdong Province, China. The climate in this region is also subtropical monsoon, with an average of annual precipitation of 1534 mm and annual temperature of 22.5 °C (both from 2004 to 2009). The acrisol soil in this area is developed from sandstone, and the soil pH is about 4.0. Due to intense human disturbances, most of native forests in this region had degraded to low-diverse plantations such as *Pinus massoniana.* Plants in this chronosequence were spaced at 3 m × 2 m from each other with *Eucalyptus urophylla* saplings after clear-cutting and prescribed burning in the same year. The oldest plantation was planted in 1984 (24-year-old plantation when the measurements were taken in 2008), while the younger ones were established in 2005 and 2006, respectively (3- and 2-year-old plantations, respectively). Fertilizers were applied at the start of planting to facilitate the establishment of saplings (500 g organic fertilizer per tree).

Experimental Design and Plant Surveys

Within each chronosequence, there were three replicate plantations for each age class. One plot was established in each plantation, which added up to 18 plots for this study. Plant diversity surveys were conducted in October 2008 at Heshan and in March 2013 at Zhangzhou, respectively. It was noted that the distance between both study sites is approximately 600 km and the time of both surveys was different. The general characteristics of the two study sites were shown in the Table 1. Surveys were conducted by the quadrat method. Specifically, a 5 m × 5 m subplot was first framed in the center of each experimental plot and then all plants over 5 cm in height within the frame were identified to the species level. Additionally, we divided target plants into three functional groups (life form): woody plants, herbaceous plants, and vine plants. All the plantation canopies were open and sunshine can easily reach understory layer in the study site (see the supplementary pictures for the 2- and 24-year-old plantations).

Data Analysis

One-way analysis of variance (ANOVA) was conducted to analyze the characteristics of plant diversity (number of family, genera, species, woody plant, herbaceous plant, and vine plant) within and between the Zhangzhou and Heshan chronosequences. Species abundance (R) was calculated by Eq. (1), where S is the number of species and N is the total number of individuals at each plot; Shannon-Wiener diversity index (H) was calculated by Eq. (2), where Pi is

Table 1 Site location and general characteristics in Heshan and Zhangzhou Eucalyptus chronosequences

Study site	Plantation age (years)	Previous forests	DBH (cm)	SOC (g kg^{-1})	TN (g kg^{-1})	C:N ratio
Zhangzhou	2	*Cunninghamia lanceolata*	9.5 ± 0.2	24.9 ± 2.0	2.1 ± 0.04	11.8 ± 0.87
	4	*Cunninghamia lanceolata*	11.7 ± 0.3	18.3 ± 0.8	2.2 ± 0.01	9.0 ± 0.32
	6	*Cunninghamia lanceolata*	13.7 ± 0.3	17.4 ± 0.6	2.0 ± 0.02	8.74 ± 0.22
Heshan	2	*Pinus massoniana*	5.0 ± 1.1	14.5 ± 1.4	0.71 ± 0.12	21.4 ± 2.0
	3	*Pinus massoniana*	6.8 ± 1.3	12.1 ± 3.2	0.49 ± 0.20	26.6 ± 3.3
	24	*Pinus massoniana*	9.9 ± 0.3	14.6 ± 1.1	1.6 ± 0.22	9.6 ± 1.7

Values are mean ± SE ($n = 3$)

DBH diameter at breast height, *SOC* soil organic carbon, *TN* total soil nitrogen, *C:N ratio* soil organic carbon:total soil nitrogen

the relative abundance of the *i*th species at each plot. All statistical analyses were carried out by SPSS 15 (SPSS, Inc, Chicago, IL) with the significant level at 0.05.

$$R = (S - 1)/\ln N \quad (1)$$

$$H = -\sum(Pi \times \ln Pi). \quad (2)$$

Detrended Correspondence Analysis (DCA) was also performed to detect the differences of species composition in both plantation chronosequences by CANOCO software for Windows 4.5 (Ithaca, NY), with eigenvalues in axis 1 and axis 2 examined. The differences of sample scores in axis 1 and axis 2 were tested with one-way ANOVA since the sample scores were evaluated by unconstrained ordination with the community data (Wu et al. 2011).

Results

Plant Diversity in the Zhangzhou Chronosequence

A total of 69 species were found in the Zhangzhou chronosequence. Specifically, a total of 40, 43, and 37 species were observed in the 2-, 4- and 6-year-old plantations, respectively. The numbers of family, genera, and species did not significantly change among plantation ages (Fig. 1). The species abundance and Shannon-Wiener index did not significantly change among plantation ages (Table 2). The total number of woody plants, herbaceous plants, and vine species in the plantation ages of 2, 4, and 6 years were 25, 21, and 17; 11, 13, and 10; and 5, 8, and 9, respectively. Furthermore, the number of three functional groups also did not differ among plantations (Fig. 2).

Plant Diversity in the Heshan Chronosequence

In total, 39 species were found in the Heshan chronosequence. There was a total of 21 species at 2-year-old, 26 species at 3-year-old, and 35 species at 24-year-old plantations, respectively. Statistical results showed that numbers of family, genera, and species did not change significantly among plantation ages of 2, 3, and 24 years, although the number of family, genera, and species slightly higher in the 24-year-old plantation than those in the 2- and 3-year-old plantations (Fig. 1). The species abundance and Shannon-Wiener index showed a similar trend with species number (Table 2).

The total number of woody species in the plantation ages of 2, 3, and 24 years was 9, 10, and 18, respectively. The herbaceous species was 9, 11, and 13, and the vine species was 3, 4, and 4 at Heshan for ages 2, 3, and 24 years, respectively. The average number of woody species in the 24-year-old plantation was significantly higher than those in the 2- and 3-year-old plantations. The number of herbaceous and vine species was not significantly altered among plantations (Fig. 2).

Plant Diversity and Composition in the Two Chronosequences

The total number of plant species was higher in the Zhangzhou Chronosequence than that in the Heshan Chronosequence. Between the two study sites, 12 co-existed species were found, which included seven woody species, four herbaceous species, and one vine species, respectively. The one-way ANOVA showed that there was no difference for number of family, genera, species, and number of vine species between the two study sites. The number of woody plants was significantly higher in the Zhangzhou site than that in the Heshan site ($P = 0.04$). In contrast, the number of herbaceous plants was significantly lower in Zhangzhou site than that in the Heshan site ($P = 0.05$) (Fig. 3).

For Heshan sites, 15 of the 21 species (71 %), 9 of the 26 species (35 %), and 11 of the 35 species (31 %) occurred in all three replicate plots to 2-, 3-, and 24-year-old plantations. Totally, 21 species were found in all three plantation ages. More than seven native woody species in the 24-year-old plantation were found than that in the 2-

Fig. 1 Numbers of families, genera, and species in the chronosequences of Zhangzhou and Heshan. Values are means + SE ($n = 3$)

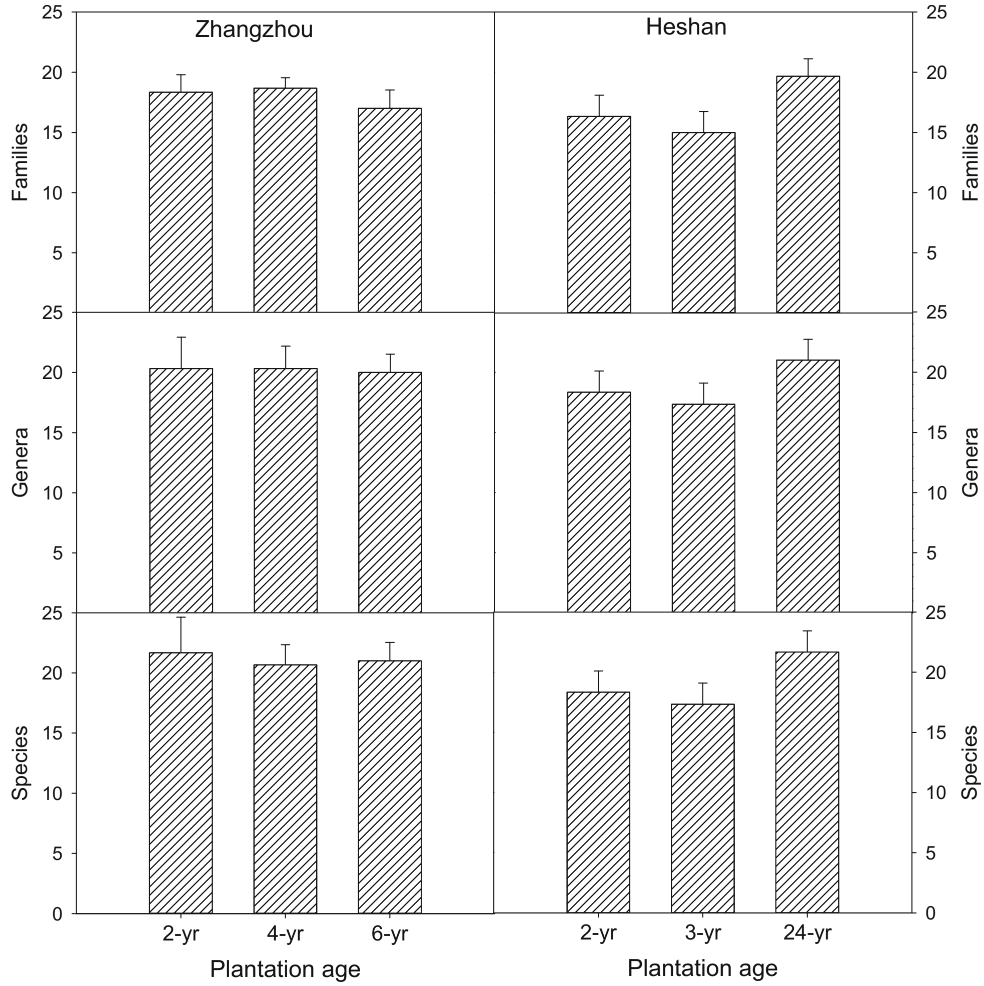


Table 2 Species abundance and Shannon-Wiener index in Heshan and Zhangzhou Eucalyptus chronosequences

Study site		Species abundance	Shannon-Wiener index
Zhangzhou	2	4.74 ± 0.49	2.74 ± 0.17
	4	4.33 ± 0.37	2.64 ± 0.12
	6	4.53 ± 0.32	2.66 ± 0.14
Heshan	2	5.95 ± 0.41	2.90 ± 0.10
	3	5.72 ± 0.42	2.84 ± 0.11
	24	6.79 ± 0.34	3.09 ± 0.07

Values are mean ± SE ($n = 3$)

and 3-year-old plantations, which were *Rhaphiolepis indica*, *Wikstroemia indica*, *Melicope pteleifolia*, *Triadica cochinchinensis*, *Rhus chinensis*, *Toxicodendron succedaneum*, *and Gardenia sootepensis*. However, for Zhangzhou sites, the percentages were only 18, 7, and 16 % to 2-, 4-, and 6-year-old plantations, respectively. Totally, 12 species were found in all three plantation ages.

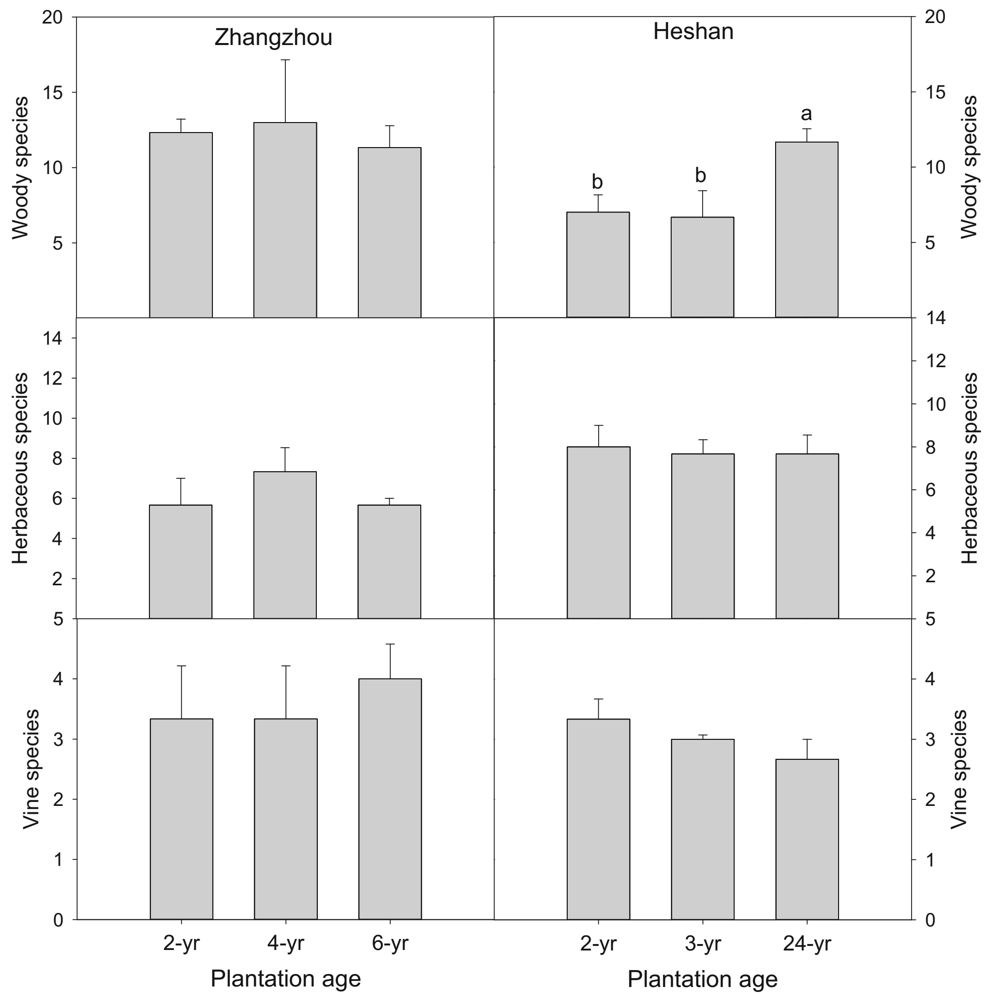
The composition of plant community in the Zhangzhou chronosequence changed significantly as the DCA result showed that the plant ordination in the 2-year-old was separated from 6-year-old and 4-year-old plantations. The sample scores showed significant difference in the first axis ($P = 0.008$). Axis 1 explained 46.1 % of the variance and axis 2 explained another 33.2 % (Fig. 4). However, the composition of plant community in the Heshan showed the obviously different between the old plantations and the young plantations (Fig. 4). The sample scores were different in the axis 1 ($P < 0.001$), suggesting the variation of plant community between young and old plantations. Axis 1 explained 28.6 % of the variance and axis 2 explained another 14.6 % (Fig. 4).

Discussion

Effects of Fast Rotation on Understory Diversity in the Zhangzhou Chronosequence

The diversity of understory plants did not vary in our experiment, which is consistent with a previous study from southwest China (Wang et al. 2011). They reported that the

Fig. 2 Numbers of woody species, herbaceous species, and vine species in the chronosequences of Zhangzhou and Heshan. The different numbers above the column mean the significant differences at $P < 0.05$ level. Values are means + SE ($n = 3$)



averaged richness and Shannon-Wiener index in Eucalyptus plantations were not significantly different with secondary evergreen forests and abandoned farmlands. In addition, Wang et al. (2011) indicated that Eucalyptus plantations reduced several woody plants compared with secondary evergreen forests, which is supported by our findings. The marginal effects of first rotation on plant diversity in the understory were also found in a 6-year-period experiment, wherein the introduced Eucalyptus did not significantly change the plant diversity (Fabião et al. 2002). The reasons for the plant diversity dynamics are unknown because few studies were conducted in these regions. We first speculated that the soil seed bank did not change in the short time-scale although some sensitive plants would disappear (Gaertner et al. 2011; Wang et al. 2011). Because the Zhangzhou chronosequence was established from native Chinese fir forests, it should have the similar soil seed bank under the same site preparation. A recent study also indicated that soil seed bank could facilitate regeneration of understory vegetation in Eucalyptus plantations in the first 3 years after afforestation (Zhang et al. 2014). Second, resources such as light and nutrients in different plantations seem similar because of the open canopy in Eucalyptus plantations and the same applications of fertilizers.

Although the first rotation of Eucalyptus plantations did not significantly affect plant diversity in the present study, we suggest cropping should be reconsidered in these regions due to the risk of losing plant diversity. For example, Wen et al. (2010) found that Eucalyptus plantations in the second rotation remarkably reduced plant richness and diversity compared with the first rotation plantations in South China. The second rotation reforestation are usually managed to get similar wood products with the first rotation. The following intense managements such as clear-cutting and prescribed burning would hinder plant regeneration and community assemblage (Proença et al. 2010; Wen et al. 2010; Wang

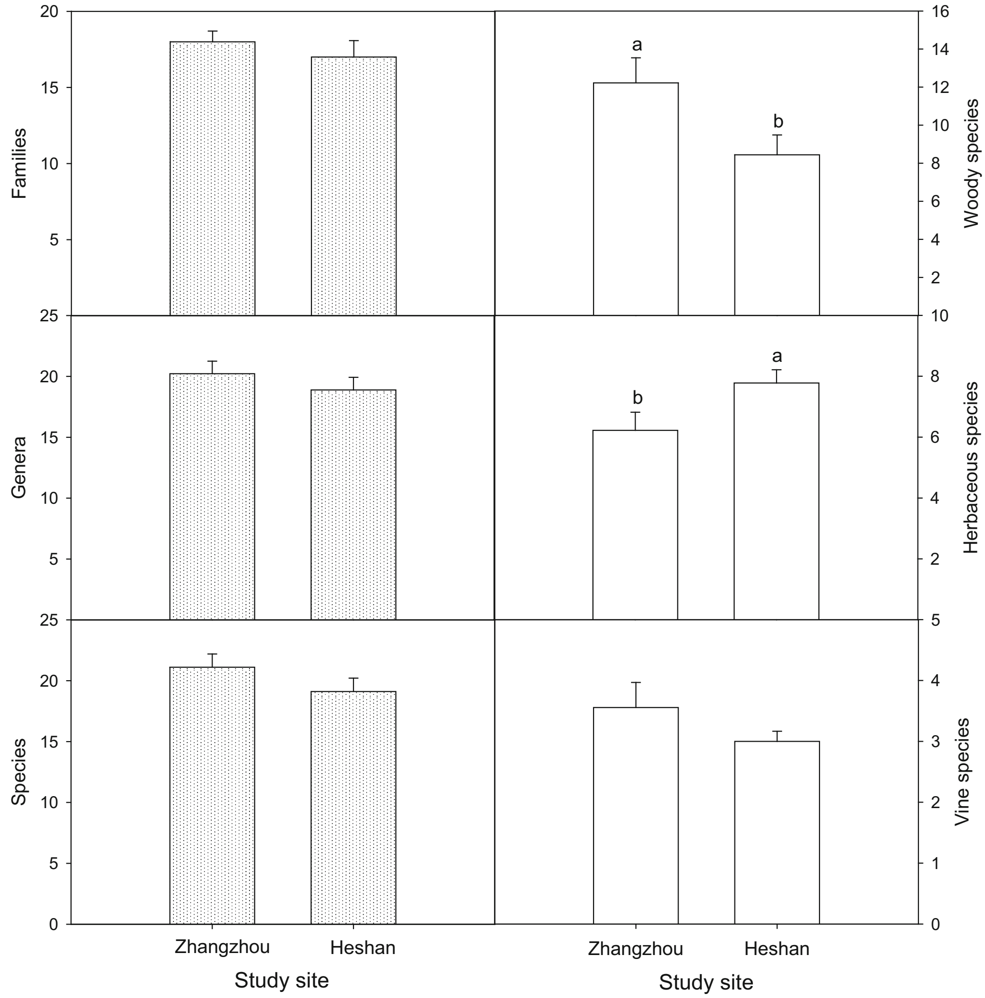


Fig. 3 The plant diversity characteristics in the chronosequences of Zhangzhou and Heshan. The different letters above the column mean the significant differences at $P < 0.05$ level. Values are means + SE ($n = 3$)

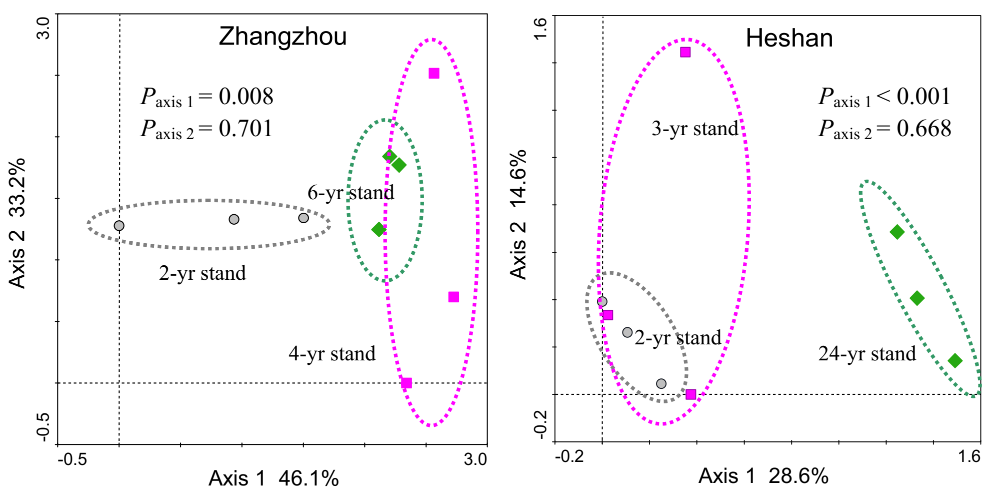


Fig. 4 Detrended correspondence analysis (DCA) of understory plant community in Zhangzhou and Heshan. The inserted P values mean the statistical analysis for the different plantation ages at axis 1 and axis 2

et al. 2013a). Moreover, capacity of soil and water conservation was worse in the Eucalyptus plantations than that in the native evergreen forest (Zhao et al. 2012b). We suggest that intercropping between exotic Eucalyptus plantations and native forests would favor native plant diversity.

Effects of Long-Term Regeneration on Understory Diversity in the Heshan Chronosequence

In the Heshan chronosequence, plantation age showed a positive effect on the diversity of understory plants, which was different with Zhangzhou chronosequence. Likewise, in an area near our experimental site in Guangdong Province, Peng (2003) found that Eucalyptus plantations established on the barren land increased understory plant diversity. In addition, the ecosystem function could be improved by planting Eucalyptus species on degraded lands, because introduction of hardy species would help turn extremely degraded lands into forests (Ren et al. 2007). A recent study also showed that facilitative effects rather competitive effects were dominant in the harsh ecosystem (Butterfield and Callaway 2013).

Our results showed that plant community composition in the 24-year-old plantations was different from those of younger plantations, which were in line with the results of plant diversity. As herbaceous species and vine species did not show significant changes among plantation ages, we attributed the change of plant composition to woody plants. Yang et al. (2009) indicated that artificial forests can facilitate growth of native species due to the nursing effect such as higher temperature buffer and radiation reduction. Consistent with this, we found that number of woody plants was higher in the 24-year-old plantation. For example, based on the total species number, there were more than seven woody species in the older plantations than the younger plantations. Several studies have shown that Eucalyptus plantations exhibited allelopathic effects on native species (Forrester et al. 2006; Gareca et al. 2007), particularly on germination during the early period (Gareca et al. 2007). However, according to our results, we reckon that the nursing effect would exceed allelopathic effect in the barren ecosystem. For example, there was low plant diversity initially and then plant diversity increased after 24 years of development in our study.

Differences of Plant Diversity Between the Two Chronosequences

It is worth noting that the number of woody was higher in the Zhangzhou chronosequence than in the Heshan chronosequence, but that of herbaceous plants was lower. We considered that the reforestation pattern and time-scale were remarkably different between the two chronosequences. For Zhangzhou chronosequence, the Eucalyptus plantations were established from native forests, where woody species could regenerate based on the existing seed bank, because the first rotation plantations would not totally destroy the seed sources. Furthermore, areas of rural forests are larger in the Zhangzhou than in the Heshan chronosequence, thereby providing potential seed sources.

By contrast, in the Heshan chronosequence, the Eucalyptus plantations were established on the severely degraded lands with low plant diversity. Unfortunately, the absence of natural vegetation nearby resulted in limited seed input, thus leading to rare woody plants in Heshan chronosequence (Wang et al. 2009). Actually, the herbaceous species would generate fast when the species richness of belowground seed bank and aboveground community is low (Ghersa and Martınez-Ghersa 2000; Zheng et al. 2004; Wang et al. 2009). In addition, the common species in the surveyed plots of each plantation age supported the higher species diversity in Zhangzhou chronosequence than in Heshan chronosequence, because the higher heterogeneous distribution of plant species usually facilitates species coexistence in the tropical forest ecosystem (Wright 2002).

Conclusions

In the fast rotation plantations, the diversity of understory plants was not quickly reduced but the extra investigation is needed for the second rotation of Eucalyptus plantations. In order to balance the pulp needs and plant diversity conservation in the fast rotation of Eucalyptus plantations, we propose that intercropping between exotic Eucalyptus plantations and native forests should be considered. Since the way of fast rotation with exotic Eucalyptus was not beneficial to the native plant diversity and system nutrient cycle (Wen et al. 2010; Wang et al. 2014). In the long-term regeneration based on barren lands, the diversity of understory plants increased, which is meaningful for ecosystem rehabilitation in the initial stage of succession due to their importance in ecosystem function and processes in subtropical regions (Wu et al. 2011; Zhao et al. 2012a). Eucalyptus may be used as the pioneer tree species to promote ecosystem functioning such as nutrient retention in poor soils (Wang et al. 2013b). Finally, the two independent experiments with different study sites and survey time showed that the understory diversity responded differently to land uses and time-scale.

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