Research paper

Comparing the Early Growth of Pure and Mixed Plantations of *Calocedrus formosana* and *Michelia formosana* at Lienhuachih, Central Taiwan

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【Summary】

In this study, we compared the early growth, in terms of the diameter at breast height (DBH) and stand basal area of *Calocedrus formosana* and *Michelia formosana* (11 yr after planting) in both even-aged monoculture and mixed plantations with 3 planting spacings at distances of 2×1, 2×2, and 2×3 m in the Lienhuachih Experimental Forest. The mixed proportion was set at 50 to 50% in the mixed plantation. In each plot, stems were tagged and identified by species, and their sizes were measured annually. Stem location was recorded on a Cartesian coordinate system. A Canon 5D camera with a Sigma 8-mm lens was used to capture a fish-eye image for the canopy analysis.

Results showed that *Michelia* grew significantly faster than *Calocedrus* in terms of DBH in 2012, and the mixed effect in the mixed plantation increased the total DBH growth of *Michelia* but decreased that of *Calocedrus*. Two periods of DBH increment indicated the superiority of *Michelia* in the 1st period but the opposite in the 2nd period. The plantation mixed effect expanded the DBH range of *Michelia* but not that of *Calocedrus*. The DBH increment was the least at the 2×1-m spacing for both species and plantation type, but there were different impacts with the wider spacing between monoculture and mixed plantations. The stand basal area in 2012 was the greatest for the 2×1-m spacing because of the larger number of trees involved, and it decreased with a declining number of trees with a wider spacing for both species and plantation types. In the mixed plantation, the proportion of the stand basal area in *Michelia* was greater reflecting the much-faster growth of *Michelia* in mixed plantations. The crown width revealed that the canopy with the 2×1-m spacing in 2012 had closed but had not closed with the 2×3-m spacing.

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研究報告

蓮華池地區肖楠、烏心石純林和人工混合林早期生長之研究

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摘 要

本報告目的是比較蓮華池試驗林2001年造林單一樹種之肖楠、烏心石人工林和兩樹種混淆人工林在2×1、2×2和2×3公尺三種栽植距離早期胸高直徑和林分斷面積之生長。試驗設計採用完全逢機設計、混淆人工林混淆比例為50和50%，以隔行混樹種方式進行混植，並在樣區內進行多年度林木屬性之調查。使用Canon 5D II全片幅機身，搭配Sigma 8 mm魚眼鏡頭進行冠層魚眼影像之拍攝和分析。

研究結果顯示到2012為止，烏心石之胸徑總生長較肖楠生長快速，混淆效應雖會增加烏心石之胸徑總生長，但會減少肖楠胸徑總生長。兩期之胸徑生長量顯示烏心石在第一期之生長明顯優於肖楠，但在第二期則不如肖楠。混淆效應擴張烏心石之胸徑範圍，但對肖楠之胸徑範圍則無影響。對兩種樹種，純林和混淆林而言，肖楠胸徑生長均以在2×1公尺栽植距離下最小，隨者栽植距離增加，在純林和混淆林間呈現不同之差異。在2×1公尺栽植距離，由於單位面積林木株數最多，使得林分斷面積最多，隨者株數減少，兩樹種和兩種人工林形態之林分斷面積，均會因栽植距離增加，有降低之趨勢。混淆林內*Michelia*較高之斷面積組成比例，反映出*Michelia*在混淆林中之優勢地位。樹冠幅顯示2×1公尺栽植距離在2012年時樹冠已開始鬱閉，但在2×3公尺栽植距離則尚未鬱閉。

關鍵詞：種間競爭、種內競爭、混淆效應、栽植密度。

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INTRODUCTION

Forest plantations are an increasingly important forest resource worldwide. In the past, most plantations were monocultures of a single species under even-aged management because of the high production of wood products. However, uniform conditions when growing a single species in large even-aged blocks may expose plantations to greater risks of biotic and abiotic damage (Man and Lieffers 1999), and problems with soil fertility (Khanna 1997). In contract, the perception persists that mixed-species plantations are more pest resistant, risk averse, or both (Montagnini et al. 1995, Ashton 2000, Vanclay 2006). Social demands for increased diversity in plantation forests may also make mixed-species plantations more attractive in the future. Maintaining and/or enhancing the mixture of tree species are now becoming main issues for developing forestry regimes to meet the demands for wood products while remaining compatible with other non-timber benefits (Yoshida and Kamitani 2000). In addition to furnishing wood products, mixed plantations can provide a more-diverse habitat for some wildlife species, such as grey squirrels; therefore, they are considered to be more natural in structure than even-aged plantations of a single species (Brown 1992). Even from a strictly timber production point of view, some mixes of species are thought to provide certain tending advantages over monocultures (West 1991, Binkley et al. 2003).

Several properties of mixed stands suggest advantages to establishing mixed plantations. Beneficial properties include possible increased growth, improved soil properties, greater insect and disease resistance, and minimization of costly intermediate silvicultural operations (Pezeshki and Oliver 1985).

Benefits of mixed-species stand systems depend on the effects of the tree species on the nutrient supply, the efficiency of the species in using nutrients, and competitive interactions for light and water (Binkley et al. 1992). However, managing mixed-species stands is more complex than managing pure single-species even-aged stands, largely because the competition process, development patterns, and treatment options of mixed-species stands are more variable that those of pure-species stands (Tilman 1987, Oliver and Larson 1996). Therefore, before large-scale mixed plantations can be considered, several characteristics such as growth habits, responses to environmental factors, and responses to competition should be investigated (Pezeshki and Oliver 1985).

Growth studies show that compared to monoculture plantations, competitions among trees of mixed-species plantings become more complex due to the increased species diversity (Lynch and Moser 1986). Beyond intraspecific competition, competition between species (i.e., interspecific) also occurs in mixed stands (Vanclay 2006). Generally, tree growth in mixed stands is governed by the mixture rate of species and the planting spacing (Shainsky and Radosevich 1992, Khanna 1997, Binkley et al. 2003, Forrester et al. 2006). Therefore, understanding the impacts of these 2 factors is a prerequisites to determining the appropriate mixing rate and planting spacing in mixed-stand management.

Many former studies on mixed plantations are available; for example, stand table predictions for 2 species groups (Lynch and Moser 1986); the effects of mixtures on growth and nutrient cycling (DeBell et al. 1989, Rothe and Binkley 2001, Binkley et al. 1992, 2003); the mechanisms of competition between 2 species (Shainsky and Radosevich 1992, Wang et al. 2004); and competition indices for mixed-species hardwoods (Holmes and Reed 1991).

In the tropics and subtropics, the long-term sustainable production of fast-growing single-species plantations is being questioned because of their effects on soil fertility (Khanna 1997). Therefore, recently, mixed plantations of fast-growing species have attracted a significant amount of attention, especially of growing mixed stands with N-fixing trees as an essential component of the mixture (DeBell et al. 1989, Wang et al. 2004). Many studies have shown increases in productivity of mixed plantations due to the better nutrient cycling of N and P and to greater light capture and light use efficiency caused by nitrogen-fixing trees as a component of mixed-species plantations (Binkley et al. 1992, Giardina et al. 1995).

Both *Calocedrus formosana* (Florin) and *Michelia formosana* (Kaneh) are very important species on Taiwanese plantations. Their high timber quality command economic value and they are respectively ranked as one of the 5 most valuable species of coniferous and broadleaf species in Taiwan (Liu et al. 1988). In Taiwan, the majority of plantations of *C. formosana* and *M. formosana* are in monoculture, and no study on the growth of mixed plantations of these 2 species has been published. The objective of this paper was to compare the growths of these 2 species in monoculture and mixed plantations under a fixed mixture proportion of the 2 species with a 50 vs. 50% framework and to investigate planting spacing effects on the early growth of pure and mixed plantations of *C. formosana* and *M. formosana* at Lienhuachih, Taiwan.

MATERIALS AND METHODS

Site description

The study site was located in No. 7 compartment at the Lienhuachih Research Center, Taiwan Forestry Research Institute, Nanton County. The elevations of the site varies 680~720 m. Based on the data collected at the meteorological station at the Lienhuachih Research Center, during 2002~2013, the yearly average temperature was 20.1℃. The annual prescription was about 2501 mm with approximately 2241 mm falling during the growing season (April~October) primarily in the summer.

Mixed and pure plantations

The mixed plantation was established in 2001. The mixed ratio proportion of the 2 species was fixed at 0.5~0.5. Three planting spacings were chosen as 2×1, 2×2, and 2×3 m which arre equivalent to 5000, 2500, and 1666 trees ha^{-1}, respectively. Each plot size is 0.0728 ha with 26 m in length and 28 m in width. Each spacing with 3 duplications was randomly assigned. Seedlings of the 2 species were simultaneously planted and alternately mixed in a line. The schemes of the plots with 3 spacings are shown in Fig. 1.

At the same site, in addition to the mixed plantations, monoculture stands (i.e., a single species) of both species with the same 3 spacing schemes mentioned above were established in 2001 as well. For the monoculture stands, the plot size was the same as that for the mixed plantations but was equally split into 2 spacings in each plot. Each spacing was duplicated 2 times in a random assignment.

Beginning in 2002, we measured the height to the tip of the dominant meristem and the diameter at the ground base of seedlings annually for each tree. Beginning in 2005, the diameter at breast height (DBH) and crown height and width were measured each year to 2012. During the 1st 3 yr, we replanted dead trees. Data from 2003 to 2012 were used for the analyses in this paper.

Fish-eye images

In 2012, a Canon 5D camera with a Sigma 8-mm lens was used to capture fish-eye images for the canopy analysis. The analysis was performed using GLA V 2.0 software. In each plot, we systematically set up 6 points and took pictures at a height of 1 m above the ground. The image was used to calculate the crown openness at each point and obtain an average for each plot (Fig. 2).

Interspecific and intraspecific competition

In order to quantify the intra and interspecific competition effects in the mixed plantations, the following equation was used (Shainsky and Radosevich 1992):

$$\ln y_i = b_0 - b_c (\ln Nc) - b_m (\ln N_m) + b_p (\ln N_c)(\ln N_m) \quad (1)$$

where y_i is the mean individual plant yield of species i by plot, b_0 is the theoretical mean

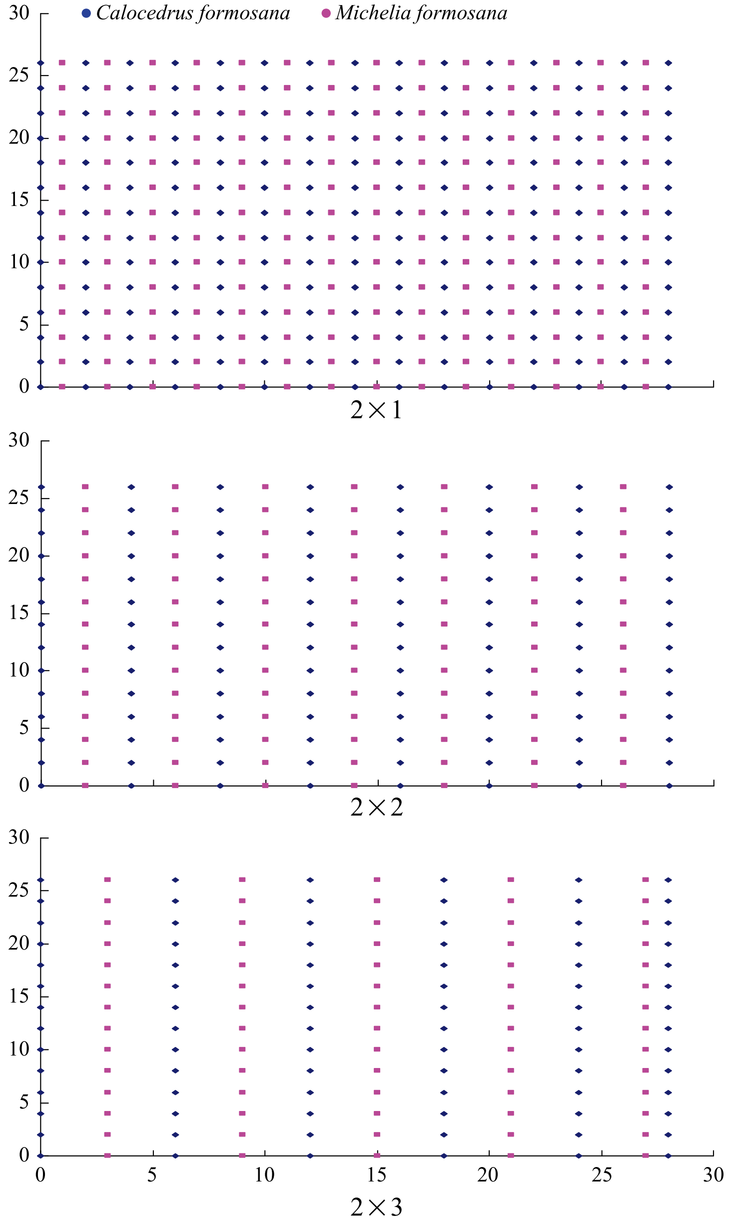
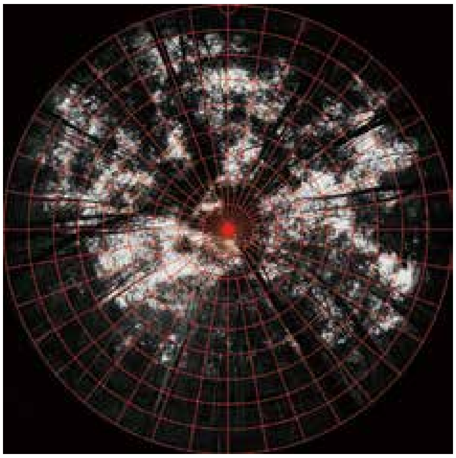


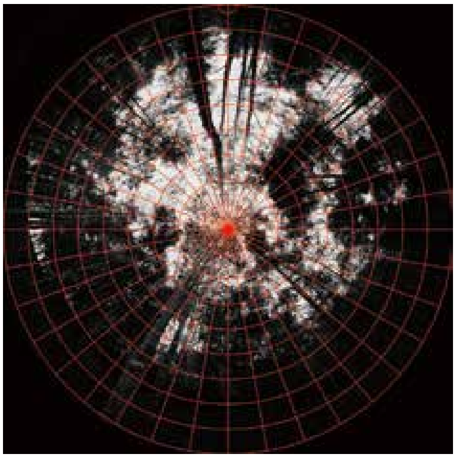
Fig. 1. Allocation of *Calocedrus formosana* and *Michelia formosana* for 3 spacings (2×1, 2×2, and 2×3 m) in mixed stands.

yield of individual plants of species under competitor-free row conditions, b_c is the regression coefficient quantifying the intraspecific effects of the spacing of *Calocedrus* (Nc) on the plant yield of species *Calocedrus* in the case of *Calocedrus*, but interspecific effects of the spacing of species *Calocedrus* on the plant yield of species *Michelia* in the case of *Michelia*, b_m is the regression coefficient quantifying the interspecific effects of the spacing of species *Michelia* (N_m) on the plant yield of species *Calocedrus* in the case of

A. 2×1-m spacing



B. 2×2-m spacing



C. 2×3-m spacing

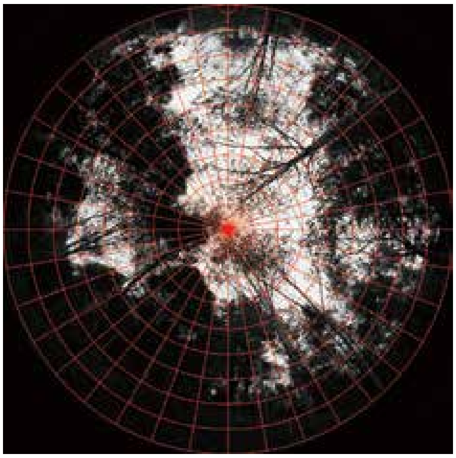


Fig. 2. Canopy openness through a fish-eye images at 3 planting spacings.

Calocedrus, but the intraspecific effects of the spacing of species *Michelia* on the plant yield of species *Michelia* in the case of *Michelia*, and b_p is the regression coefficient quantifying the effect of the product of the densities on *Calocedrus* and *Michelia*.

Practically, if the regression coefficients obtained in equation (1) are not significant at the 95% confidence level, an option suggested by Shainsky and Radosevich (1992) was used to fit 2 single competitions (equation 2 and 3) for each species separately in the following equations:

$$\ln y_i = b_0 - b_c (\ln Nc) \quad (2)$$

$$\ln y_i = b_0 - b_m (\ln N_m) \quad (3)$$

where y_i, b_0, b_c, b_m, Nc, and N_m are the same as mentioned in equation (1).

RESULTS AND DISCUSSION

Pattern of mortality

In this study, survival rates in 2006, 2009, and 2012 were used to investigate the effects of the treatments on the survival rate. Survival rates remained quite stable from 2006 to 2012 for most treatments (Table 1). Overall, even though the survival rate of *Michelia* trees was slightly higher than that of *Calocedrus* trees and the mixed plantations had slightly lower survival rates, no significant differences were detected in the corresponding treatments ($p > 0.05$). In this study, because we wanted to analyze the periodic growth in 2003~2012, all one-line boundary data in the plot and inconsistent data in this period were deleted. Approximately, 81% of the data from surviving trees were used for the subsequent analyses.

Characteristics of total growth in 2012

Overall, very significant differences occurred between the 2 species in DBH (9.8 vs. 7.9 cm, $p < 0.0001$), individual tree basal area

Table 1. Survival rates in 3 periods in pure and mixed plantations for 2 species

Spacing	Survival rate in 2006 (%)	Survival rate in 2009 (%)	Survival rate in 2012 (%)
2×1 m	94.5 (5.1)	93.1 (5.4)	91.5 (5.1)
Calocedrus	93.2 (5.3)	91.8 (2.5)	89.9 (5.2)
pure	94.0 (6.9)	92.9 (2.3)	90.6 (3.5)
mixed	92.1 (5.7)	90.4 (2.8)	88.9 (4.1)
Michelia	95.8 (3.5)	94.1 (7.3)	92.6 (4.8)
pure	96.5 (4.9)	94.9 (6.3)	92.7 (4.5)
mixed	94.7 (3.9)	93.5 (2.7)	92.5 (2.9)
2×2 m	93.5 (4.4)	92.1 (7.9)	90.1 (9.4)
Calocedrus	92.9 (5.6)	90.5 (6.2)	88.9 (8.3)
pure	94.5 (1.9)	92.2 (5.3)	89.4 (7.7)
mixed	91.6 (7.5)	89.3 (7.6)	86.9 (8.3)
Michelia	94.0 (3.2)	92.6 (9.3)	91.2 (9.2)
Pure	95.0 (1.7)	93.9 (9.7)	91.8 (2.3)
mixed	93.5 (3.3)	91.8 (8.9)	90.4 (15.3)
2×3 m	93.2 (6.8)	92.3 (6.6)	91.5 (6.9)
Calocedrus	93.9 (7.2)	92.5 (8.7)	90.3 (8.4)
pure	93.8 (8.4)	92.3 (9.8)	90.2 (9.3)
mixed	92.4 (5.8)	91.8 (7.1)	90.7 (8.1)
Michelia	94.7 (4.5)	93.6 (3.1)	92.4 (3.8)
pure	94.1 (2.5)	92.3 (5.1)	90.5 (3.3)
mixed	95.7 (5.8)	95.2 (3.6)	94.1 (2.2)

Figures in parenthesis are the standard deviations.

(0.0086 vs. 0.0056 m^2, $p < 0.0001$), and tree crown (2.23 vs. 2.11 m, $p < 0.0001$) in 2012. In general, the DBH of *Michelia* trees grew faster than that of *Calocedrus* (e.g., 9.2 vs. 6.7 cm at 2×1 m, 10.5 vs. 9.0 cm at 2×2 m, and 10.5 vs. 9.2 cm at 2×3 m, Table 2). As to plantation types (pure/mixed), while differences occurred between species (Table 2), an ANOVA showed that the total growth of DBH in mixed plantations was significantly higher than that in pure plantations for species and spacing combined (9.0 vs. 8.5 cm, $p < 0.0001$).

Due to the existence of a strong interaction between species and plantation type ($p < 0.0001$), the mixed effects in plantations differed between the 2 species. For example. at a spacing of 2×1 m, the mixed effects of plantations increased the total DBH growth of *Michelia* trees (7.4 vs. 10.2 cm, $p < 0.0001$), but decreased the total growth of *Calocedrus* (8.4 vs. 5.7 cm, $p < 0.0001$). This means that for *Calocedrus*, the associated negative mixed effect reduced its total growth, whereas, for *Michelia*, the mixed effect was positive. The tendency for a mixed effect on species in term of DBH was the same for the other 2 spacings (Table 2).

In both plantations types, significant differences with respect to species, planting spacing and plot location occurred in the total growth of DBH in 2012 ($p < 0.0001$). Therefore, averages of replications were used for each treatment in species, plantation type, and planting spacing. Generally, in mixed plantations, the total growth in DBH of *Michelia* was significantly higher than that of *Calocedrus* for all planting spacings (10.9 vs. 7.3

Table 2. Characteristics of attributes of 2 species in pure and mixed plantations and 3 spacings in 2012

Spacing	DBH (cm)	Basal area (m^2 ha^{-1})	Crown width (m)
2×1 m	7.8 (3.4)	16.44 (2.06)	1.99 (0.65)
Calocedrus	6.7 (2.6)	13.28 (1.98)	1.92 (0.69)
pure	8.4 (2.4)	23.85 (2.83)	1.83 (0.59)
mixed	5.7 (2.1)	6.23 (1.42)	1.97 (0.74)
Michelia	9.2 (3.9)	19.03 (2.12)	2.09 (0.59)
pure	7.4 (3.1)	19.21 (1.55)	2.04 (0.65)
mixed	10.2 (3.9)	18.91 (2.50)	2.11 (0.55)
2×2 m	9.7 (3.5)	12.45 (1.00)	2.30 (0.69)
Calocedrus	9.0 (3.0)	11.26 (0.96)	2.03 (0.46)
pure	9.6 (3.4)	17.72 (1.85)	1.97 (0.64)
mixed	8.7 (2.7)	6.96 (0.37)	2.07 (0.33)
Michelia	10.5 (4.0)	13.42 (3.06)	2.60 (0.79)
pure	8.1 (3.4)	12.76 (4.62)	2.69 (0.80)
mixed	11.7 (3.6)	13.87 (2.02)	2.55 (0.78)
2×3 m	9.8 (3.6)	9.82 (2.01)	2.52 (0.86)
Calocedrus.	9.2 (3.3)	8.95 (1.72)	2.47 (0.81)
pure	9.2 (3.4)	13.72 (1.43)	2.20 (0.49)
mixed	9.2 (3.2)	5.77 (1.92)	2.48 (0.80)
Michelia	10.5 (3.8)	10.53 (2.24)	2.76 (0.80)
pure	9.2 (3.2)	12.80 (1.85)	2.85 (0.74)
mixed	11.4 (3.9)	9.01 (2.50)	2.68 (0.84)

Figures in parenthesis are standard deviations for three replications in mixed plantations, and two replications in pure plantations under 3 spacings.
DBH, diameter at breast height.

cm, $p < 0.0001$), because of the rapid early growth of *Michelia.* Consequently, *Calocedrus* trees were dominated by *Michelia* trees due to the strong interspecific competition between the species. Differences in DBH total growth between the 2 species in mixed plantations were very significantly affected by spacing ($p = 0.0001$) at 4.5 cm at a 2×1-m spacing, which then declined to 3.0 cm at a 2×2-m spacing and 2.2 cm at a 2×3-m spacing (Table 2). In other words, stronger interspecific competition stresses from *Michelia* than weaker intraspecific competitions by *Calocedrus* caused the growth of *Calocedrus* to be substantially inhibited by the presence of *Michelia* as neighbors. With an increasing distance among neighbors, however, interspecific competition stresses gradually declined, and therefore, the difference between the species was reduced as well.

Pattern of diameter growth

In this study, two 4-yr increments (i.e., 2003~2007 and 2008~2012) were calculated to compare 4-yr increments in DBH and basal area. Growth in the 1st period was significantly higher than that in the 2nd period ($p < 0.0001$) in DBH in both species, because of the more-intensive competition that occurred in the 2nd period for the 2 plantation types and 3 planting spacings. Totally, the DBH growth for the 2 periods of *Michelia* was superior to that of *Calocedrus* ($p < 0.0001$) in terms of species, and better growth in mixed- than that in single-species plantations ($p < 0.0001$) in terms of plantation types (Fig. 3).

In the 1st period, DBH increments of *Michelia* were very significantly ($p < 0.0001$) higher than those of *Calocedrus* for both plantation types (i.e., average DBH increments of DBH for *Michelia* and *Calocedrus* were 5.9 vs. 4.1 cm in pure plantation and 6.5 vs. 3.0 cm in mixed plantations) at a 2×1-m spacing. This trend held for the other 2 spacings (Fig. 3). Overall, the mixed effect significantly increased the DBH increment (5.3 vs. 4.9 cm, $p = 0.0001$), but the influence differed between species. For *Michelia*, the mixed effect accelerated the periodic increment at all planting spacings with the largest amount (6.5~5.8 = 0.7 cm) at the 2×1 m spacing. On the contrary, for *Calocedrus*, the mixed effect reduced the periodic increment most (4.1 - 3.0 = 1.1 cm) at the 2×1-m spacing with a minor influence at wider planting spacings (Fig. 3).

In the 2nd period, it was obvious that, in general, DBH increments during this period were lower than these in the 1st period because of the more-intensive competition commencing in the 2nd period (Fig. 3). In contrast to the 1st period, the DBH increment of *Calocedrus* was significantly larger than that of *Michelia* in the 2nd period (3.9 vs. 3.3 cm, $p < 0.0001$), indicating that *Michelia* encountered more-serious competition than did *Calocedrus* in the 2nd period. Generally, the mixed effect turned out to be adverse to the DBH increment in the 2nd period because of the more-complicated competition that existed in the mixed plantations.

In terms of species, the DBH increment reduction in the 2nd period in *Michelia* was significantly greater than that in *Calocedrus* (1.9 vs. 1.0 cm, $p < 0.0001$) for both

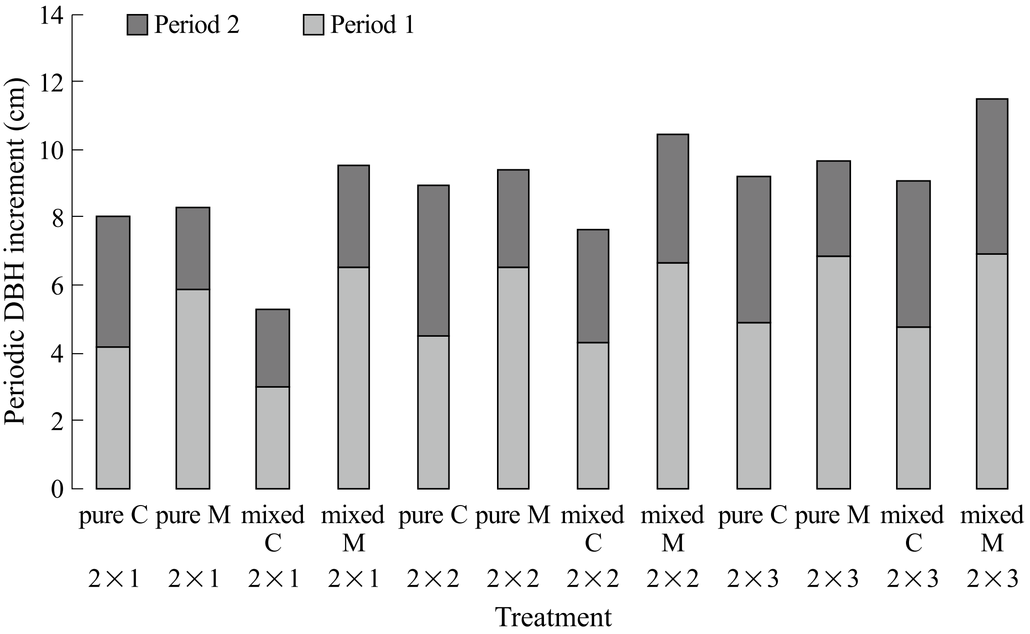


Fig. 3. Diameter at breast height (DBH) periodic increments among treatments. C, *Calocedrus formosana*; M, *Michelia formosana*; pure, monocultural plantation; mixed, mixed-species plantation.

plantation types and spacings combined. This means that in the 2nd period, *Michelia* suffered from more-serious competition than did *Calocedrus*. In the mixed plantation, reductions between the 2 periods in *Michelia* were substantially higher than these in *Calocedrus* (e.g., 2.9 cm for *Michelia* and 1.2 cm for *Calocedrus* in the combined data for all spacings) owing to the relatively intense intercompetition that occurred in *Michelia*.

Overall benefits from the mixed-species plantations depend on a suite of factors that probably substantially differ across sites and species (Parrotta 1999). This study showed that the DBH increment in the 2nd period was differently affected by the mixture between *Calocedrus* and *Michelia*. For the former, the increment in the 2nd period in mixed plantations was lower than that in pure plantations (e.g., an average of 3.3 cm in mixed plantations vs. an average of 4.6 cm in pure plantation for combined spacing data); however, in the latter, the same data revealed that the mixed effect increased the increment from an average of 2.7 cm in the pure plantations to an average of 3.8 cm in mixed plantations. While both interspecific and intraspecific competition occurred in mixed plantations, the mixed effect depended on the composition of species (Weiskittel et al. 2011). In our case, because the interspecific competition between species was asymmetrically demonstrated by the superior growth of *Michelia* to that of *Calocedrus*, the interspecific competition caused by *Michelia* was adverse to *Calocedrus.* On the contrary, interspecific competition caused by *Calocedrus* was favorable to *Michelia*, because it replaced the intraspecific competition among same-species neighbors in the next line just as the case in pure *Michelia* plantations.

In this study, the 2nd periodic increment was used to separate the total periodic increments into increments by DBH classes (Fig. 4). Results showed that the DBH increment in the pooled data had a high positive correlation (Pearson value 0.70, $p = 0.0001$) with initial DBH sizes. In mixed plantations, increments at a given DBH size between the 2 species depended on their relative advantages in the population. For *Calocedrus*, 95% of trees had a DBH range of 2~8 cm, whereas, for *Michelia*, 44% of trees had a DBH of > 8 cm at the 2 × 1-m spacing. This means that a tree with a DBH of 6 cm may be considered to be a medium-large tree in the *Calocedrus* population, but perhaps it was a small-medium tree in the *Michelia* population. Despite increments in DBH classes ranging 2~8 cm in *Michelia* being lower than those of trees at the same DBH range in *Calocedrus* (Fig. 4), the added increments obtained from trees with a DBH of > 10 cm made the total increment of *Michelia* higher than that of *Calocedrus* (Table 2, Fig. 3). Similar results were observed for the other 2 densities.

From an ecological theoretical point of view, interference among species growing in mixtures is a combination of 2 processes, facilitation and competition (Kelty 1989, Radosevich et al. 2006). In a mixture of Douglas-fir and red alder, both processes were evident at a site with the lowest fertility (Shainsky and Radosevich 1991, D'Amato and Puettmann 2004, Radosevich et al. 2006). With *Michelia*, this study shows that mixed plantings reduced the strong competition from intraspecific trees, but added weak competition from interspecific trees. Overall, the combined competition was accordingly reduced. However, with *Calocedrus*, the combined competition was not reduced. As neither species was a nitrogen-fixing species, facilitation interactions were not shown in this study.

Owing to less interspecific competition imposed by *Calocedrus*, the growth of *Mi-*

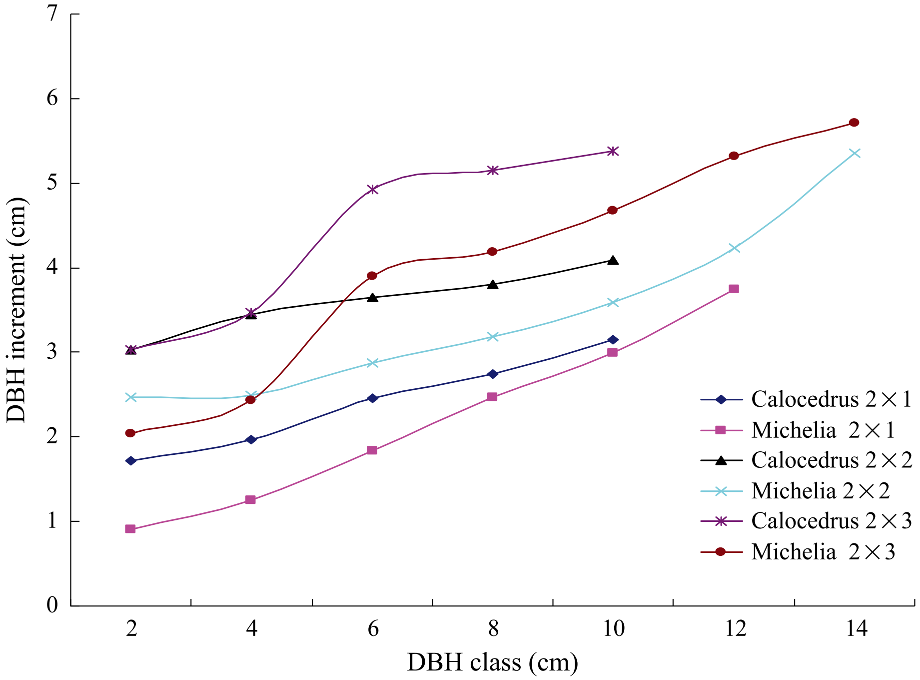


Fig. 4. Diameter at breast height (DBH) increment among DBH classes in mixed plantations in the 2nd periodic increment.

chelia trees became more vigorous in mixed plantations, and therefore, the DBH range of *Michelia* was expanded. The DBH range, for instance, was 2~10 cm in the pure plantation, but was 2~12 cm with the 2×1-m spacing in mixed plantation. Expansion of the DBH range increased at wider spacings (2~10 to 2~14 and 2~12 to 2~14 cm at spacings of 2×2 and 2×3 m, respectively). This finding supports mixed *Eucalyptus* stands increasing the DBH range compared to the case of monocultures (Binkely et al. 2003). However, due to being in a weak position in competition with *Michelia*, the same DBH class ranges (2~10 cm) for pure and mixed plantations was observed for *Calocedrus* at all 3 spacings (Fig. 4).

The distribution of diameter classes in plantations also differed among species and planting spacings. With *Calocedrus*, the proportion of trees of a small size (e.g., DBH of 2~6 cm) was higher than that of a big size (e.g., DBH of 8~12 cm) for all spacings and 2 types of plantation, suggesting that most of the DBH increments in *Calocedrus* was concentrated on small trees. In contrast, in *Michelia*, the DBH increments was negatively skewed toward to big trees for both plantation types and 3 spacings. This contrast in DBH classes supported the DBH increment in *Michelia* being larger than that in *Calocedrus* (Fig. 3). In addition to the variety of DBH range, the DBH class with the highest frequency of trees also differed between species. For *Calocedrus*, the class in question was 6 cm for all spacings, but it was 8 cm for all spacings for *Michelia*. The adverse effect of the mixed effect on *Calocedruds* was the worst (i.e., it reduced the DBH class with the greatest frequency of trees from 6 to 4 cm) at the 2×1-m spacing, but no difference was found at the other 2 spacings (Table 3).

Table 3. Diameter at breast height (DBH) range and DBH class with the most frequency of trees in the 2nd periodic DBH increment

Spacing	Forest type	Species	DBH range (cm)	DBH class with the most number of stems (cm)
2×1 m	Pure	*Calocedrus formosana*	2~10	6
		Michelia formosana	2~12	8
	Mixed	*Calocedrus formosana*	2~10	4
		Michelia formosana	2~14	8
2×2 m	Pure	*Calocedrus formosana*	2~10	6
		Michelia formosana	2~12	8
	Mixed	*Calocedrus formosana*	2~12	6
		Michelia formosana	2~14	10
2×3 m	Pure	*Calocedrus formosana*	2~10	6
		Michelia formosana	2~14	8
	Mixed	*Calocedrus formosana*	2~10	6
		Michelia formosana	2~14	10

Shainsky and Radosevich (1992) demonstrated that interspecific and intraspecific competition effects could be quantitatively identified in alder and Douglas-fir mixed plantations. In this study, due to the small sample size, few planting spacings, and the variation among plots, interspecific and intraspecific competition could not be integrated into a single regression (i.e., neither coefficient was significant at the 95% confidence level); thus, only single competition could be separately identified for both species (Shainsky and Radosevich 1992). For *Calocedrus*, the resulting 2 regressions were ln (DBH) = 6.41 – 0.621×log (number of trees ha^{-1} of *Calocedrus*), and ln (DBH) = 5.61 – 0.520×log (number of trees ha^{-1} of *Michelia*). For *Michelia*, the corresponding 2 regressions were ln (DBH) = 7.62 – 0.746×log (number of trees ha^{-1} of *Calocedrus*) and ln (DBH) = 6.86 – 0.653×log (number of trees ha^{-1} of *Michelia*), respectively. Although we could not directly compare coefficients of the number of trees of the 2 species to determine the intensity of inter and intraspecific competition because of different values of the regression constant (Shainsky and Radosevich 1992), together with observations of benefits obtained in the growth of *Michelia* and the loss in *Calocedrus* caused by the mixed effect (Figs. 3, 4), it seems reasonable to infer that interspecific competition was stronger than intraspecific competition for *Calocedrus*, but was the opposite for *Michelia.*

Patterns of stand basal area growth

As in the case of DBH, the same trends of individual basal increments with respect to all treatments were observed. In order to investigate the mixed effect on the basis of the total amount per hectare, the stand basal area was calculated as well. Basically, the stand basal area is affected by the basal area growth of individual trees and also by the number of trees in a stand (Clutter et al. 1983). The stand basal area in 2012 indicated that in pure and mixed plantations, the stand basal area was highest at 2×1 m because of the greatest number of trees involved, and the stand basal area decreased with a decreasing number of trees with a wider spacing among individuals (Table 2).

In mixed plantations at a given spacing, the proportion of the basal area of *Michelia* was greater than that of *Calocedrus*, which reflected the overwhelmieng growth of *Michelia* in mixed plantations. However, the proportion rates of the 2 species differed among planting spacings. In the most-crowded plantations, due to strong interspecific competition, trees of *Calocedrus* were suppressed by their *Michelia* competitors; consequently, a large contrast in basal area occurred (composition proportion 75 vs. 25% at the 2×1-m spacing). However, with a wider spacing, more resources obtained by trees reduced the interspecific competition between the 2 components; thus, the corresponding ratios became 67 vs. 33% at the 2×2-m spacing and 61 vs. 39% at the 2×3-m spacing (Table 2).

Compared to the pure plantations, the mixed plantation reduced the species component of the stand basal area for both species due to the decline in the number of trees in mixed plantations at a given spacing. However, overall, the mixture effect increased the total stand basal area in mixed plantations compared to that in pure plantations for both species and all spacings (Table 2). This result confirmed the higher production in mixed plantations (Khana 1997, Pretzsch et al. 2013).

In addition to the overall stand basal area in 2012, the periodic stand basal area increment (m^2 ha^{-1}) was investigated as well. Generally, the 2nd basal area increments were larger than those in the 1st period for all treatments because of the increasingly rapid growth beginning in the 2nd period ($p <$ 0.0001) (Fig. 5). In pure plantations, the total basal area increment in *Michelia* was slightly lower than that in *Calocedrus* (11.90 vs. 14.81, p = 0.01); however, the trend was substantially reversed in mixed plantations (11.81 vs. 5.39, p = 0.0001) due to its superiority of *Micheliain* individual tree growth by *Calocedrus* for all spacings combined. Overall, the total stand basal area increment was the highest at 2×1 m for both species and declined at the other 2 spacings because of the lower number of trees with a greater spacings. In mixed plantations, the superiority of *Michelia* decreased as the spacing became wider (Fig. 5).

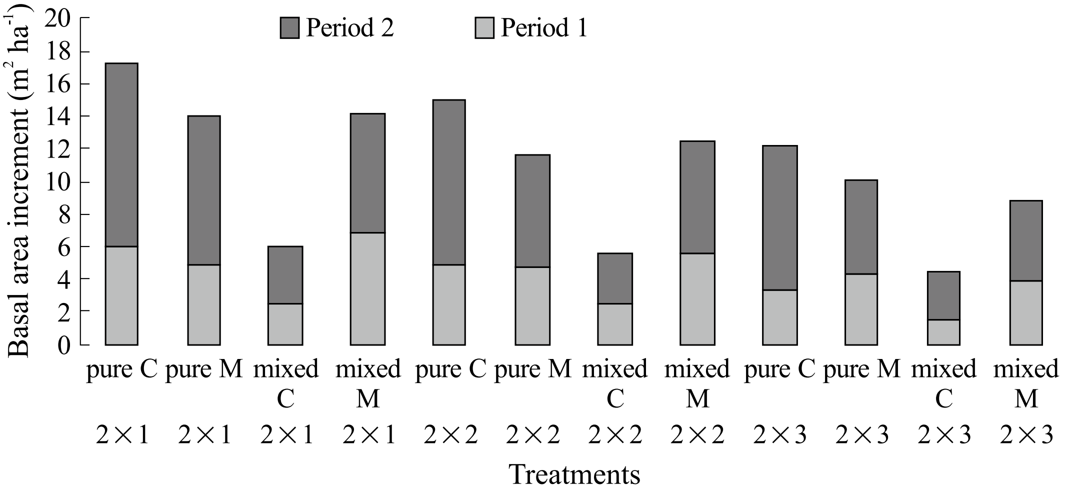


Fig. 5. Basal area increments by treatments. C, *Calocedrus formosana*; M, *Michelia formosana*; pure, monocultural plantation; mixed, mixed-species plantation.

Individual tree basal area growth showed a positive correlation with the initial basal area. The same trend as DBH growth occurred in the expansion of the basal area range imposed by the mixture of species in both species (e.g., the associated initial DBH ranged 2~10 cm in pure plantations vs. 2~12 cm in mixed stands for *Calocedrus* and 2~14 vs. 2~16 cm for *Michelia*) (Fig. 6). In this study, since the basal area increment per hectare at a given DBH class was controlled by the number of trees in that DBH class and its potential growth, for a given DBH, we did not compare basal area growth among different planting spacings. Instead, we compared the highest basal area growth DHB class for each treatment. With respect to species, due to the slower growth of *Calocedrus*, its highest basal area growth was in a DBH class which was smaller than that of *Michelia* for both pure (6~8 vs. 8~10 cm) and mixed plantations (6~8 vs. 10 cm). Expansion of the DBH class given the highest basal area growth by the mixed effects varied between species and among planting spacings. In *Calocedrus*, no change in the DBH class was observed at any spacing; however, a change in the DBH class occurred in *Michelia* at the 2×1-m spacing (8 vs. 10 cm), with no change occurring at the 2×2- (10 vs. 10 cm) or 2×3-m (10 vs. 10 cm) spacings.

At 2×1 m spacing, the DBH class with the highest basal area growth was smaller (6 cm) for *Calocedrus* than for *Michelia* (8 cm in the pure and 10 cm in the mixed plantations). No difference was observed between 2×2 and 2×3 m for pure and mixed plantations in either species (8 cm for *Calocedrus* and 10 cm for *Michelia*) (Fig. 6).

Crown openness and crown width

Fish-eye images were used to calculate crown openness (Fig. 2). Generally, the crown openness for *Michelia* was bigger than that for *Calocedrus* because of a difference in the crown shape between the 2 species. In 2012, in the mixed plantations, there was a significant difference in crown openness among planting spacing (F = 12.88, p = 0.0001). Among them, the crown openness was largestt (23.44%) at 2×3 m followed by 20.03%

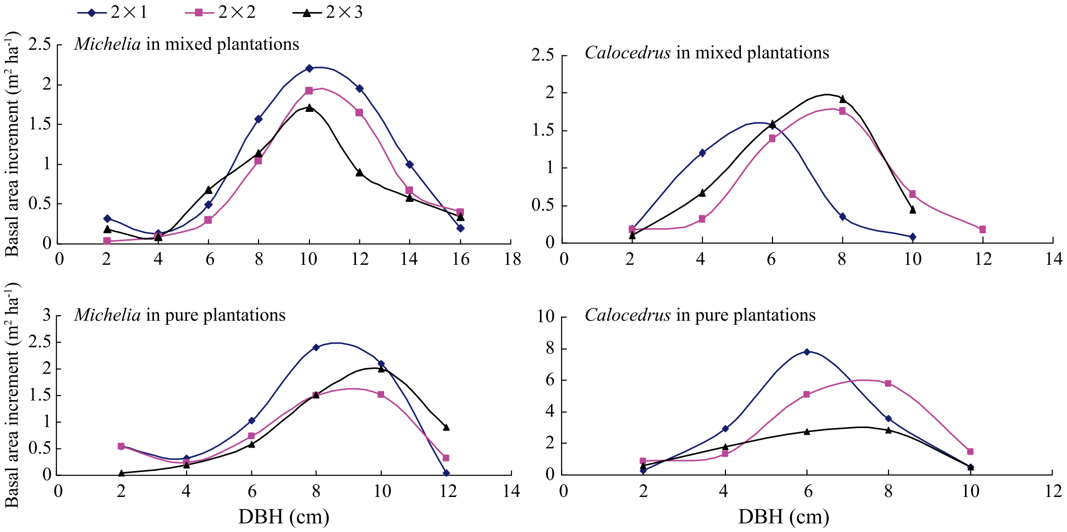


Fig. 6. Basal area increments among diameter at breast height (DBH) classes for 3 planting spacings.

at 2×2 m and 17.61% at 2×1 m spacing. The same trend with respect to spacing was true for pure plantations of both species.

In addition to crown openness, we used crown width to evaluate if the canopy was closed or not. Overall, at the 2×1-m spacing, the verage crown width in 2012 was significantly > 1 m (1.9 m, $p < 0.0001$) for species and stand types combined with the fact that the branches of trees at this spacing were connected to each other (i.e., the canopy was closed); therefore, strong competitions had already occurred among trees. However, at the 2×3-m spacing, the average crown widths was < 3 m for all cases, implying that in 2012, the plantation canopy was still not in a closed form for all cases; consequently, slight competition was occurring (Fig. 7).

In terms of species, the crown width of *Michelia* was significantly wider than that of *Calocedrus* (2.3 vs. 2.0 m, $p < 0.0001$) because of the faster growth of the former at all spacings. This study showed that crown width became significantly larger as the space increased for both plantation types ($p < 0.0001$) (Fig. 7).

Planting spacing effect

Trees in plantations compete with each other for resources (light, water, and nutrients); therefore, competition among individuals was affected by the space shared by individuals. In order to distinguish the stand type, spacing effects were analyzed in both pure and mixed plantations. Generally, in pure plantations, the overall DBH growth in the 2 periods was significantly affected by the spacing ($p < 0.0001$), with the least at 6.4 cm at a 2×1-m spacing for species combined, and increases to 8.8 cm at 2×2 m and 9.2 cm at 2×3 m for the species combined. In mixed plantations, the DBH growth was still significantly less (9.2 cm) at a 2×1-m spacing, but there was no apparent difference between the other 2 spacings (11.2 at 2×2 m and 10.8 at 2×3 m) for the species combined. In other words, with the spacing design considered in this study, spacing had different influences on wider spaces between pure and mixed plantations.

For stand basal area growth, the total amount of basal area growth in the 2 periods at the 2×1-m spacing was significantly higher than those in the other 2 spacings because of the abundant trees in the plantation ($p = 0.001$). However, it became weak with wider spacing with no significant difference between the 2 wider spacings.

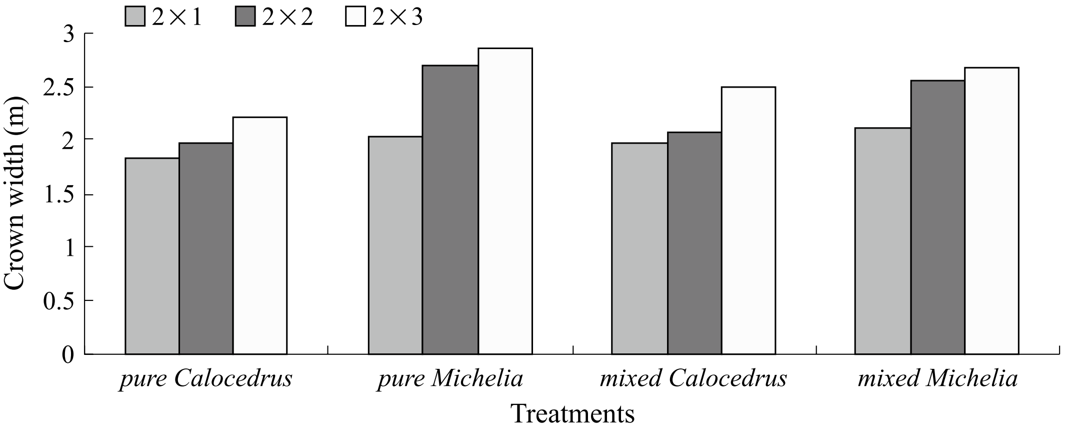


Fig. 7. Tree crown width in 2012 among 3 planting spacings for 2 species.

CONCLUSIONS

Three issues of monoculture and mixed plantations (i.e., species, mixed effect, and planting spacing) were addressed in this study. We examined the early growth (e.g., the 1st decade) of *Michelia* and *Calocedrus* in monoculture and mixed plantations. Results showed that the mixed effect influenced both species in different ways. In mixed plantations, the precedence of *Michelia* in basal composition at a 2×1-m spacing implied that competitions between species may lead to changes in the original mixed plantations to monoculture plantations in basal composition in the future. But, the mixed share of basal area may continue at both the 2×2- and 2×3-m spacings. However, more data on a longer period are required to validate this inference.

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