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Effect of the lateral growth rate on wood properties in fast-growing hardwood species

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Abstract We investigated the feasibility of using several fast-growing tropical or subtropical hardwood species for timber production by measuring key wood qualities in relationship to the high rates of lateral growth. The trees tested were sampled from even-aged plantations of *Acacia mangium*, *A. auriculiformis*, hybrid *Acacia* (*A. mangium* × *A. auriculiformis*), *Eucalyptus grandis*, *E. globulus*, and *Paraserianthes falcataria* (Solomon and Java origin) that had already reached commercial harvesting age. The released strain of the surface growth stress (*RS*), xylem density (*XD*), microfibril angle (*MFA*), and fiber length (*FL*) were measured at the outermost part of the xylem at breast height in each tree. Results were then compared to the lateral growth rate (radius/age) at breast height, which provides a relative indicator of the amount of tree growth per year. Our findings indicated that *RS* was constant, regardless of lateral growth rate in each species. Similar results were observed for *XD*, *MFA*, and *FL*, with a few exceptions, suggesting that high growth rates do not intrinsically affect the wood properties of fast-growing tropical or subtropical species that have reached harvesting age. However, special attention must be paid to patterns of xylem maturation when developing plantations of such species.

Key words *Paraserianthes falcataria* · *Eucalyptus* · *Acacia* · Growth stress · Tropical · Plantation

Introduction

Plantation cultivation of fast-growing species has been developed in tropical and subtropical countries. It arrests the downward trend of tropical forest areas, because the rate of growth or biomass production in fast-growing tropical species is often several times or even ten times greater than that of commercial species in temperate zones.[1] Implementation of plantation planting of fast-growing species is expected to have a great effect in mitigating increasing atomospheric carbon dioxide (CO_2) by acting as a massive sink.

Plantations of fast-growing species were initially developed mainly for the rapid supply of raw material to the charcoal or pulp industries.[2] Consequently, fast-growing species may not produce benefits as satisfactory as those of traditional timber species.[3] Thus, the resources of fast-growing species remain underutilized, and it is suspected that the growth in plantation planting of fast-growing species may plateau in the near future. If this view is correct, the key lies in how to increase economic incentives for developing plantations of fast-growing species. This change becomes possible if the resources harvested from such plantations can be supplied to the global market as added-valued products, such as timber materials for building or for furniture.

Some people consider that the high growth rate of fast-growing species has some negative effects on wood qualities, including decreased xylem density, shortening of fiber length, and generation of large growth stress, among others.

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This perception is a problem that limits the utilization of fast-growing tropical species as timber materials, although the concerns over wood quality have not yet been verified, except in a limited number of studies.[4–11]

The question over the wood properties of fast-growing species thus remains unresolved. For this report, we conducted a comparative study of the wood properties of several fast-growing plantation hardwood species in relationship to their lateral growth rate. The plantations examined had already reached commercial harvesting age. In this study, we aimed to determine whether the high growth rate in fast-growing species does in fact affect the wood properties (surface growth stress, xylem density, fiber length, and microfibril angle) at the surface of the stem.

Materials and methods

Plant materials

Trees of three genera (*Acacia, Eucalyptus, Paraserianthes*) were examined in even-aged plantations in Malaysia, Australia, and Indonesia, respectively. The conditions of the sampling areas are as follows:

1. *Acacia* spp.
   - *Acacia mangium* Willd.: Forty trees were tested from an 11-year-old plantation (planted in July 1988 and harvested in June 1999) in Kinalut village near Kota Kinabalu (5.93° N 116.00° E) in Sabah Province, Malaysia.
   - *A. auriculiformis* A. Cunn. ex Benth.: Forty 11-year-old trees were tested from the same plantation as *A. mangium*.
   - Hybrid *Acacia* (*A. mangium* × *A. auriculiformis*): Forty 11-year-old trees were tested from the same plantation as *A. mangium*.
2. *Eucalyptus* spp.
   - *Eucalyptus globulus* Labill.: Thirty trees were sampled from each of two 11-year-old plantations (planted September 1990, harvested September 2001) in Augusta (34.19° S 115.09° E), Australia.
   - *E. grandis* W. Hill ex Maiden: Thirty trees were tested from a 14-year-old plantation (planted November 1986, harvested September 2000) in Gympie (26.11° S, 152.38° E), near Brisbane, Australia.
3. *Paraserianthes falcataria* (L.) Nielsen
   - Solomon origin: Fifty trees were tested from a 7-year-old plantation (planted November 1996, harvested December 2003) in Pare village near Surabaya (7.17° S, 112.45° E) in East Java Province, Indonesia.
   - Java origin: Fifty trees were tested from an 8-year-old block (planted November 1996, harvested January 2005) in the same plantation as the Solomon origin samples.

All the trees tested were originally grown in seedling plantations and had been well managed in the silvicultural sense until harvesting age was reached. In all cases specimens with straight trunks and of varying diameter were selected to obtain a representative population.

Various material parameters were measured at the four cardinal points at the breast height on each tree. The longitudinal released strain (*RS*) of the surface growth stresses was first measured. A rectangular specimen was then collected at the point where the *RS* was measured, and this specimen used to measure xylem density (*XD*), fiber length (*FL*), and microfibril angle in the middle layer of the secondary wall (*MFA*). Large growth stress (longitudinal component) often causes processing defects, including heart checking and end splitting at felling, lumber crooking during sawing, and cleavage of drying lumber.[12–14] *XD*, *MFA*, and *FL* are responsible for determining the mechanical strength and the dimensional stability of the wood in a complementary manner.[15,16]

The values measured at the four cardinal points were averaged for each tree. Results were compared with the lateral growth rate (= radius/age) at the breast height of the tree in each plantation, which gave a relative indicator of the amount of tree growth per year.

Longitudinal released strain of the growth stress (*RS*)

The longitudinal released strain of the surface growth stress (*RS*) was used as an evaluation index of the longitudinal growth stress, as in previous studies.[17,18]

Measuring points were set at the four cardinal points around the periphery in each standing stem, at breast height. After exposing the outermost surface of the secondary xylem at each measuring point, a strain gauge (electric wire strain gauge, 10 mm length; Kyowa) was pasted on to each measuring point along the longitudinal direction, using a quick-dry glue, and connected to a strain meter (UCAM-1A; Kyowa). After measuring the initial strain on the stumpage, the surface stress was released using a handsaw, and the strain was recorded. The amount of the longitudinal released strain of growth stress was calculated by subtracting the initial measurement from the second reading.[19–22]

Xylem density (*XD*) at the air-dried condition

We measured air-dried xylem density (*XD*) on the surface of the xylem for all the test specimens of *P. falcataria* and *Eucalyptus* spp. and for selected specimens from each of the species of *Acacia*.

After measuring the surface released strain, a small rectangular portion was taken from each measuring point and trimmed to form a small cubic specimen (1 × 1 × 1 cm). These specimens were seasoned at room temperature inside a small air-conditioned desiccator containing a saturated aqueous solution of NaCl until air-dried. The air-dried volumes of these specimens were determined by the mercury displacement method using the law of flotation; the air-dried weight was then divided by this volume to derive the air-dried density (*XD*).[15]

Microfibril angle in the middle layer of the secondary wall (*MFA*)

Microfibril angle (*MFA*) on the surface of the xylem was determined for all test specimens of *Eucalyptus* spp. and for selected trees from each of the other species. Following the measurement of *XD* made as already described, a 0.1-mm-thick tangential section was taken from each cubic specimen. *MFA* in a thin tangential section was determined with the modified Cave's method using X-ray diffractometry (XD-D1w; Shimadzu).[23,24]

Fiber length (*FL*)

Fiber length (*FL*) on the surface of the xylem was measured for all *P. falcataria* and *Eucalyptus* spp. trees tested, and for selected trees from each of the *Acacia* spp.

After the measurement of *XD*, part of each cubic specimen was macerated in a compound liquid of water, potassium chlorate, and 60% nitric acid; isolated fibers were then dispersed in an aqueous suspension of water. For all species except Java origin *P. falcataria*, a small drop of this suspension was mounted on a glass slide, which was then cover-slipped. Microscopic images of each slide were then transferred to a personal computer equipped with image-processing software. For each specimen, 50–60 undamaged fibers were randomly selected on the PC monitor by the naked eye, and the length of each fiber then measured semiautomatically. In case of Java origin *P. falcataria*, samples of suspension containing many fibers were directly transferred to a Fiber-Quality-Analyzer (High Res. FQA; OpTest Equipment), and 5000 fibers were measured automatically for each block specimen.

Results and discussion

Longitudinal released strain (*RS*)

In the present study, the *RS* was contractive for virtually all the trees tested. This result indicates that tensile surface stresses were usually generated in the direction parallel to the fiber axis in each tree. Averaged values of *RS* in each species tested are listed in Table 1, and compared to *RS* in typical temperate species grown in Japan, as reported by Sasaki et al.[19] It is evident that the absolute values of *RS* are generally higher in the fast-growing species than in the typical commercial species grown in the Japan temperate

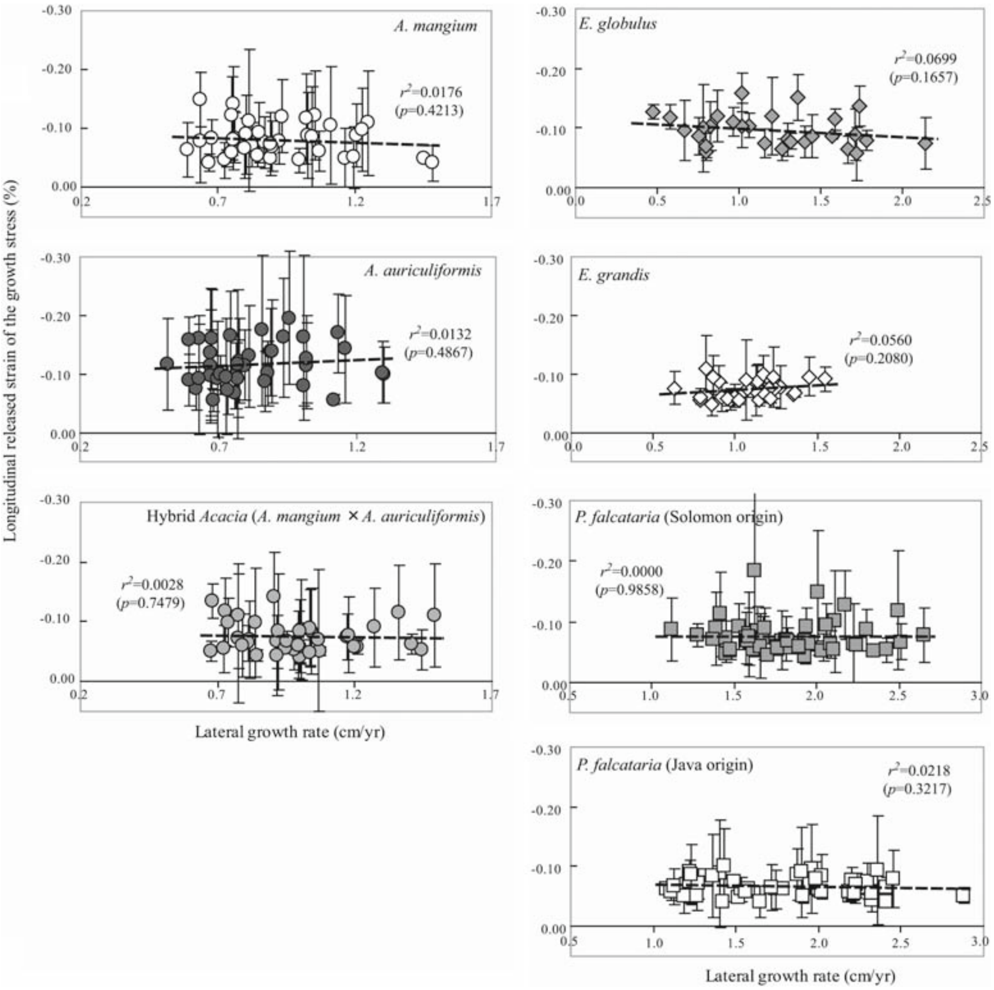


Fig. 1. Relationship between lateral growth rate and longitudinal released strain (*RS*) of surface growth stress for various species. r^2 is the contribution ratio and P is the probability of realization of the null hypothesis ($r^2 = 0$), calculated by Student's *t* test. Each *bar* represents ± 1 SD

Table 1. Averaged released strain of surface growth stress (*RS*), xylem density (*XD*), microfibril angle (*MFA*), and fiber length (*FL*) in each species

Species	*RS* (%)		*XD* (g/cm^3)		*MFA* (deg.)		*FL* (mm)	
	Average	Min. – Max.[a]	Average	Min. – Max.[a]	Average	Min. – Max[a]	Average	Min. – Max.[a]
A. mangium	–0.0803	–0.0007 to –0.2732	0.683	0.479–0.852	13.8	8.8–21.6	1.071	0.903–1.219
A. auriculiformis	–0.1163	0.0345 to –0.3005	0.696	0.461–0.819	13.2	7.2–23.4	1.126	0.972–1.233
Hybrid *A.* (*A. mangium* × *A. auriculiformis*)	–0.0747	0.0249 to –0.2426	0.583	0.435–0.738	12.1	7.2–19.8	1.143	0.999–1.284
P. falcataria (Solomon origin)	–0.0755	–0.0058 to –0.3186	0.357	0.235–0.509	10.0	0–19.4	1.125	0.978–1.344
P. falcataria (Java origin)	–0.0673	–0.0041 to –0.2309	0.391	0.210–0.631	12.4	7.3–17.6	1.200	1.074–1.371
E. grandis	–0.0726	–0.0127 to –0.1900	0.664	0.408–0.819	13.9	5.8–21.9	1.125	0.968–1.334
E. globulus	–0.0964	–0.0119 to –0.2121	0.796	0.511–1.020	6.9	0.9–14.6	1.158	0.969–1.391
Japanese trees[b]	–0.043	–0.020 to –0.100						
Acer saccharum[c]			0.56	0.45–0.67			0.92	0.13[e]
Fraxinus americana[c]			0.6	0.48–0.72			1.26	0.17[e]
Populus tremuloides[c]			0.35	0.28–0.42			1.32	0.22[e]
Betula pendula[d]					–	9.4–18.3		
Eucalyptus delagatensis[d]					–	8.5–20.0		
Populus deltoides[d]					–	14.1–18.4		

A., Acacia; P., Paraserianthes; E., Eucalyptus

[a] Minimum and maximum values from all measurement points

[b] Calculated from data for 12 species from Sasaki et al.:[19] *Cryptomeria japonica*, *Pinus densiflora*, *Ilex pedunculosa*, *Ilex macropoda*, *Ilex integra*, *Magnolia obovata*, *Magnolia praecocissima*, *Quercus serrata*, *Quercus crispula*, *Zelkova serrata*, *Carpinus tschonoskii*, *Prunus donarium*

[c] Diffused porous wood species: value of *XD* is in temperate regions reported by Haygreen and Bowyer[29] and *FL* by Panshin and de Zeeuw[30]

[d] Diffused porous wood species[31]

[e] Standard deviation

zone. Furthermore, very large contractive released strains of –0.15% to –0.30%, which are typical *RS* values in tension wood in general, were measured at some points in each species,[25] even though most of the trees tested had straight stems.

Figure 1 shows the relationship between the lateral growth rate and the average *RS* in each species. No correlation was observed between the lateral growth rate and the averaged *RS* in any species. These results support previous reports that the lateral growth rate does not affect the longitudinal growth stress of *A. mangium*,[7] *P. falcataria*,[8] or *E. grandis*.[9] However, they contradict the findings of Wilkins and Kitahara that the growth stress of *E. grandis* became somewhat smaller with increase in stem diameter,[5,6] and the report of Hillis that the growth stress in some *Eucalyptus* species increases slightly with lateral growth rate.[26] Among the species tested, *E. globulus* showed a weak negative correlation between the lateral growth rate and the *RS*; this lends some support to Wilkins and Kitahara.[5,6] In either case, it is reasonable to conclude that accelerated lateral growth does not intrinsically affect the longitudinal growth stress of fast-growing species.

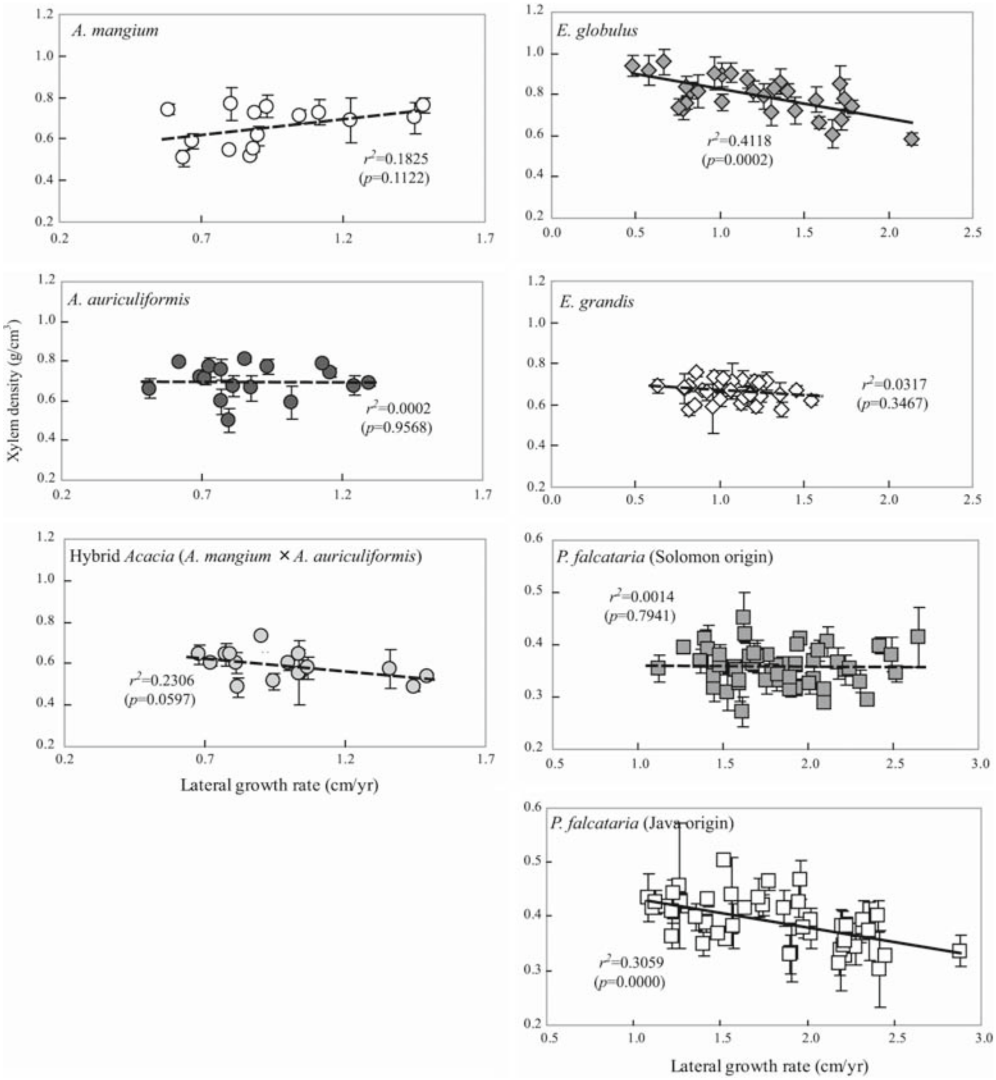
Xylem density (*XD*) at the air-dried condition

Averaged values of air-dried density in each tested species are listed in Table 1, compared to *XD* in three typical temperate genera (*Acer*, *Fraxinus*, and *Populus*). The *XD* in the fast-growing plantation species spans a wide range, from 0.357 g/cm^3 (*P. falcataria*, Solomon origin) to 0.796 g/cm^3 (*E. globulus*), and varies according to species even in the same genus; for example, *XD* in *E. globulus* is considerably higher than that in *E. grandis*. Those species stand comparison with commercial timber species in temperate regions as regarding *XD*.

We compared *XD* with the lateral growth rate for each species (Fig. 2). The individual plots show the relationship between lateral growth rate and averaged *XD* in each tree tested of each species. No correlation was observed between the lateral growth rate and the averaged *XD* for any species except *P. falcataria* (Java origin) and *E. globulus* (Fig. 2). This finding suggests that acceleration of lateral growth does not decrease *XD* at the outermost surface of the xylem.

P. falcataria (Java origin) and *E. globulus* showed negative correlations (**$P < 0.01$) between lateral growth rate

Fig. 2. Relationship between lateral growth rate and air-dried density (*XD*) at the outermost surface of the xylem for various species. r^2 is the contribution ratio and P is the probability of realization of the null hypothesis ($r^2 = 0$), calculated by Student's *t* test. Each *bar* represents ± 1 SD



and *XD*. For these species, the faster the growth, the smaller the *XD* becomes. As to the case of *P. falcataria* (Java origin), we can obtain another perspective, that the plantation of *P. falcataria* (Java origin) is divided into two groups based on the lateral growth rate around 1.8–2.0 cm/year; i.e., the fast-growing group with a comparatively lower *XD* and the slow-growing one with a higher *XD*. From this perspective, it can be said that the trees of the fast-growing group in *P. falcataria* (Java origin) are more or less same as those in *P. falcataria* (Solomon origin) in terms of the *XD*. However, we cannot give a rational explanation why the plantation of *P. falcataria* (Java origin) could be divided into the aforementioned two groups. Also regarding *E. globulus*, it is still difficult to explain the origin of the negative correlations between lateral growth rate and *XD*.

Microfibril angle (*MFA*)

Averaged *MFA* values for each species are listed in Table 1. In the same manner as for *XD*, *MFA* in the fast-growing plantation species spans a wide range among the tested species, from 6.9 degrees (*E. globulus*) to 13.9 degrees (*E. grandis*).

The relationships between the lateral growth rate and the *MFA* in each species are illustrated in Fig. 3. Clear positive correlation was observed between lateral growth rate and *MFA* in *E. globulus* (**$P < 0.01$). However, no significant correlation between lateral growth rate and *MFA* was observed for any of the other species, indicating that in these cases acceleration of secondary growth does not affect the *MFA* at the outermost surface of the xylem. As is the case with negative correlation between lateral growth rate and *XD*, it is still difficult to explain the origin of the positive correlation between lateral growth rate and *MFA* in *E. globulus*. In either case, the slow-glowing tree often showed high *XD* and low *MFA* in the *E. globulus* plantation. There might be some causal relationship between both qualities in a small-diameter tree, e.g., formation of the tension wood fiber with a thick gelatinous layer and low *MFA*, as pointed by Washusen et al.[27]

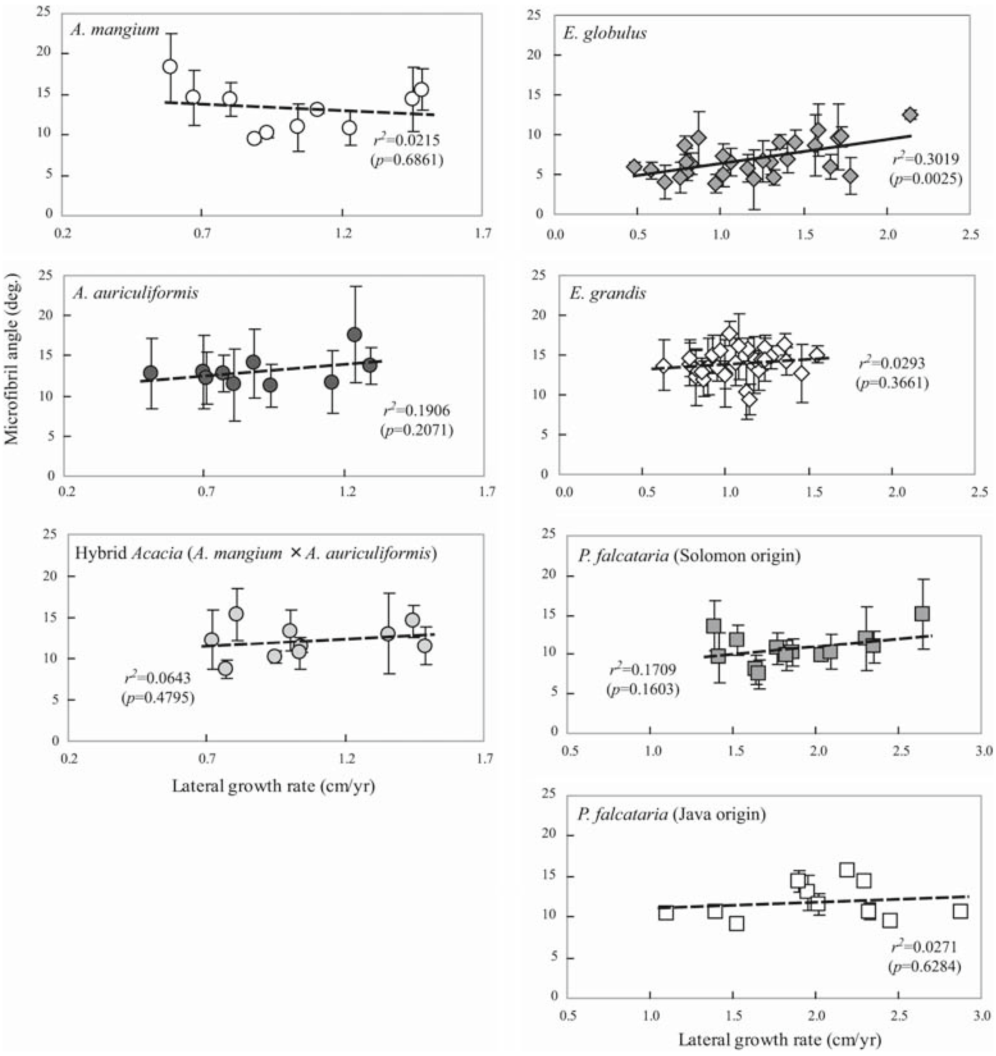


Fig. 3. Relationship between lateral growth rate and microfibril angle (*MFA*) at the outermost surface of the xylem for various species. r^2 is the contribution ratio and *P* is the probability of realization of the null hypothesis ($r^2 = 0$), calculated by Student's *t* test. Each *bar* represents ± 1 SD

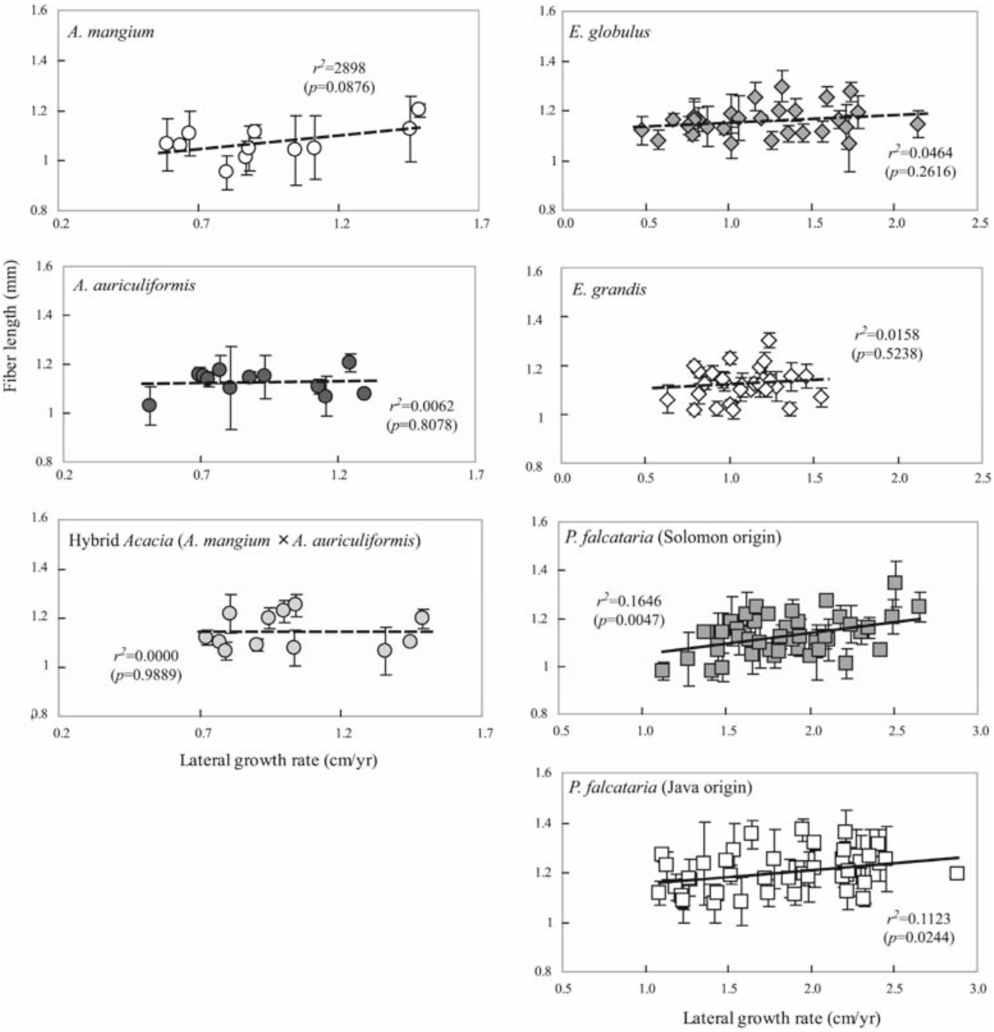


Fig. 4. Relationship between lateral growth rate and fiber length (*FL*) at the outermost surface of the xylem for various species. r^2 is the contribution ratio and *P* is the probability of realization of the null hypothesis ($r^2 = 0$), calculated by Student's *t* test. Each *bar* represents ± 1 SD

Fiber length (*FL*)

Averaged values of *FL* in each species are listed in Table 1. In contrast to the results for *RS*, *XD*, and *MFA*, average *FL* is more or less the same for all species. The measurement of *FL* usually gave a standard deviation around 10% of the average in each specimen.

The relationships between the lateral growth rate and the *FL* in each species are illustrated in Fig. 4. Positive correlations were observed for *P. falcataria* (**$P < 0.01$ for Solomon origin; *$P < 0.05$ for Java origin), whereas no correlation was seen in the others. In either case, acceleration of secondary growth does not cause deterioration of *FL* at the outermost surface of the xylem in those species.

In our separate experiment using the same plantations as in the present study, we investigated the maturation properties of the fast-growing species by analyzing an increasing pattern of *FL* from the pith to the outermost xylem, and we found that formation of mature wood started after a certain diameter was reached in *Acacia* spp. and *P. falcataria*, and that the width of the juvenile wood zone was narrower in *Acacia* spp. than *P. falcataria*.[28] The diameter of the juvenile wood zone was estimated as 17.1 cm (± 5.1) in *A. mangium*, 22.4 cm (± 5.9) in *A. auriculiformis*, 38.9 cm (± 10.3) in *P. falcataria* (Java origin), and 35.3 cm (± 8.2) in *P. falcataria* (Solomon origin), and the value of fiber length in the mature wood region was almost the same in each species.[28] Thus, it is considered that small-diameter trees were still in the course of xylem maturation in *P. falcataria*; this would be the reason why the *FL* in *P. falcataria* showed a clear positive correlation with lateral growth rate. Thus, in the case of *P. falcataria* it would be preferable to accelerate their lateral growth to produce longer fibers via silvicultural treatment, e.g., planting distance and thinning intensity; however, in that situation attention would need to be paid to attendant lowering of *XD* in Java origin *P. falcataria* (see Fig. 2). If the wood qualities would be controlled by a genetic basis aside from growing conditions, we need to select the plus-trees that generate smaller *RS*, smaller *MFA*, higher *XD*, and the longest *FL*.

Conclusions

Here, we investigated the feasibility of using fast-growing species for timber production. We focused on the effect of lateral growth rates on various wood properties at the outermost surface of the secondary xylem of several even-aged, fast-growing plantation species that had reached commercial harvesting age. Our results indicated that the released strain of the surface growth stress was constant, regardless of lateral growth rate in each species. Similar results were observed for xylem density, microfibril angle, and fiber length, with a few exceptions. From these findings, we concluded that rapid rates of lateral growth do not intrinsically affect the wood qualities of fast-growing tropical and subtropical species. However, the xylem was still immature in small-diameter trees in certain species; thus, special attention should be paid to the maturation properties of xylem when plantations of these species are developed.

Our results also indicated that the wood quality of the tested fast-growing species was not inferior to traditional temperate timber species, except that the absolute value of *RS* was generally higher in the fast-growing species than in the commercial species grown in the Japanese temperate zone. From these results, we concluded that the fast-growing species have ample potential for use in the production of timber materials, at levels similar to traditional timber species. However, when using fast-growing species, attention must be paid to the possibility for high tensile growth stress, which can often cause processing defects.

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