Effect of Initial Planting Density and Tree Features on Growth, Wood Density, and Anatomical Properties from a *Hevea brasiliensis* Trial Plantation

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Abstract

The effect of initial planting density (500, 1,000, 1,500, and 2,000 trees per ha) on tree growth, wood density, and wood anatomical properties was studied in a 9-year-old *Heave brasiliensis* plantation in Malaysia. Results showed that effects of initial planting density on tree radial growth, wood density, fiber length, fiber wall thickness, and ray density were more visible in trees planted at 500 trees per ha compared with the other planting densities. Bole length was significantly increased with higher planting densities. However, vessel density showed an infinite pattern with increasing planting density. For vessel and ray areas, no significant effect of initial planting density was detected. A negative relationship was observed between wood density, fiber length, and fiber wall thickness with planting density, bole length, and height-to-diameter ratio. The ray density was significantly and positively correlated with stand/tree features with the exception of a negative correlation with radial growth increment. The regression models with various degrees of goodness of fit indicated that wood density followed by fiber wall thickness was successfully quantified due to selected stand/tree features. According to the results of this study, it is recommended that a low planting density of 500 trees per ha is ideal for rubberwood plantation development.

During the past decades, wood production strategy has shifted from natural forests to plantation forests. The role of forest plantation in meeting future wood and fiber demands will increase in the near term, irrespective of rates of forest plantation establishment (Brown 2001, Alfred 2007). Fast-growing and high-yielding species are important sources of wood in the tropical regions (Pérez Cordero et al. 2003). Large areas of natural forests are likely to present an advantage in the short term, but that advantage will finally decline as a result of better advantages offered by the plantations, that is, the ability to grow identical trees quickly in available areas (Brown 2001). The rubber tree (*Hevea brasiliensis*) native to the Amazon forests of Brazil is one of the most important species for forestation in tropical areas. Rubberwood plantations in Malaysia are expanding with a current total area of about 1.1 million hectares (Hance 2010).

Many silvicultural techniques are being practiced to improve the productivity and wood quality of forest plantations in accordance with intensive forest management

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(Jiang et al. 2007). Effective stand management involves controlling the spacing of the growing stock. Control of stand density by varying planting density and thinning intensity has been a major tool in regulating tree growth and wood quality (Kenk 1990). Different silvicultural management strategies produce variations in wood properties. In tropical fast-grown plantations, most workers are looking for an association between growth rate and wood quality of xylem (Ishiguri et al. 2011). In spite of the wide variety of studies that have determined the effect of initial planting density on wood characteristics, such as wood density (Weber and Sotelo Montes 2010) and wood anatomical properties (Lin and Chiu 2007, Tu Kim et al. 2011), a generalization on the effect of initial planting density on wood quality has not yet been set up because of different responses in wood quality characteristics to planting density, individual reactions of each species, and the influence of environmental conditions (Zobel and Van Buijtenen 1989).

To the best of our knowledge, no specific research has been carried out on fundamental rubberwood properties, and the relationship between silvicultural techniques and wood quality characteristics has hardly been quantified.

The main objectives of this study were twofold. First, we aimed to measure the effects of initial planting density on tree growth, wood density, and wood anatomical characteristics in a 9-year-old pilot plantation of *H. brasiliensis*. Second, we intended to create models to predict wood density and anatomical characteristics in accordance with tree and stand features in order to allow direct assessment of wood quality in standing trees.

Materials and Methods

Study site and sample preparation

The rubberwood (*H. brasiliensis*) disks used in this study were obtained from a 9-year-old pilot plantation (latitude 5°45′0″N and longitude 102°30′0″E) in the state of Terengganu, Peninsular Malaysia. A flat terrain plantation of about 3 ha with four different planting densities was established in the year 2000 to simulate growth rate and wood quality. The mean annual precipitation recorded during the last 3 years was 3,752 mm (Weather Report 2009). The initial planting density (PD) varied from 500 (PD I) to 1,000 (PD II) to 1,500 (PD III) to 2,000 (PD IV) stems per ha (trees per hectare) of clone RRIM 2025. Two 5-cm disks along the tree stem were harvested at a height of 1.3 m from four trees from each of the four planting densities (with a total of 16 trees). The disks were labeled, wrapped in black plastic bags, and transported to the wood anatomy laboratory for further analyses.

The rubber tree clone RRIM 2025 that was examined in this study is Latex Timber Clone (LTC) from RRIM 2000 series. This clone produces high latex yield and has vigorous growth, suitable for timber production (Malaysian Rubber Board 2003). The basic information on tree growth information is presented in Table 1. The diameter at breast height (DBH), clear bole length (BL; length until the first living branch underneath the crown), and height-to-diameter ratio (HD) of 30 trees from each PD were measured. From the standpoint of tree development in the wood industry, growth ring width is usually referred to as growth rate. Owing to unclear growth rings in rubber trees (Nobuchi et al. 1995, Lim et al. 2003, Honjo et al. 2005), the mean radial growth increment (RGI) was calculated by the mean DBH divided by the age of the stand (age, 9 y). The RGI shows a proportional measurement of the radial growth rate (Zobel and Van Buijtenen 1989) as a simple parameter to verify growth at a specific age (West 2006). As rubber trees grew tall, measuring height of trees under intensive planting densities was difficult. Therefore, the tree height measurement was ignored (Rodrigo et al. 2004) and instead, the clear BL was chosen for further survey.

Air-dry WD

In this study, the measurement of air-dry wood density (WD) was centered for the investigation because it is more practical compared with the other types of wood density measurements and the results are closer to the natural condition. Wood sampling method and general requirements for physical tests were carried out in accordance to ISO standard 3129-1975 (E) (International Organization for Standardization [ISO] 1975a). ISO 3131-1975 (E) (ISO 1975b) was used to measure the WD. A diametric segment 20 mm wide and 50 mm in height was cut through and through from the disk. This segment was cut from height into three different strips. After rejecting the pith area, the strips were continuously cut into small blocks with no interval between them. Because of the small DBH of the sampled trees and in order to have more sample blocks as well as increasing test accuracy, the dimensions of the blocks were modified to 15 by 15 by 15 mm. Ninety-six sample blocks from disks from PD I and 72 sample blocks from disks from each of the remaining planting densities were prepared. After measurement of WD, the average values taken for each PD were compared with values of other planting densities. WD was calculated according to the air-dry weights upon the corresponding volumes. The air-dry volume was determined using the water displacement method.

Microscopic images and cell morphology measurements

Wood block samples measuring 15 by 15 by 15 mm were prepared from pith to bark of each segment. Transverse sections 15 to 20 μm thick were prepared from the blocks by a sledge microtome. The sections were then stained with 1 percent safranin and dehydrated in an alcohol series. Dehydrated sections were put in clove oil for 1 minute and then mounted on glass slides with Distyrene-plasticizer-xylene.

In order to measure fiber features, some matchstick size splinters were carefully cut from the central part of each sample block with a sharp knife and were then macerated with a mixture of 1.5 g of sodium chlorite in 25 ml of distilled water and eight drops of acetic acid for a period of about 48 hours. After that, macerated specimens were carefully rinsed using distilled water. Free individual fibers were kept in glycerin before examination under microscope. Measurements of all wood anatomical characteristics were carried out using the Leica Image Analysis System (QWin model). The fiber length (FL; micrometers) and fiber wall thickness (FWT; micrometers) were measured from haphazardly selected fiber cells. A magnification of ×100 was used to measure FL, while a magnification of ×400 was used to measure FWT. The FL was measured by digitizing the tip-to-tip length of straight and unbroken fibers. Fifty

Table 1.—Basic information on tree growth in the four planting densities of Hevea brasiliensis.[a]

Clone	PD (trees/ha)	Sym.	pd (m)	DBH (cm)[b]	BL (cm)	H (m)	HD (m/cm)	RGI (cm)
RRIM 2025	500	I	4.0 × 5.0	20.0 (2.8) A	738 (121) C	14.9	0.38 (0.07) B	2.2 (0.25) A
	1,000	II	4.0 × 2.5	16.3 (2.7) B	788 (77) C	21.0	0.49 (0.09) B	1.8 (0.25) B
	1,500	III	3.0 × 2.2	15.3 (3.0) B	909 (98) B	22.1	0.61 (0.11) A	1.7 (0.26) B
	2,000	IV	2.0 × 2.5	15.1 (3.4) B	1,026 (107) A	21.6	0.70 (0.14) A	1.7 (0.27) B

[a] PD = planting density; Sym. = symbol; pd = planting distance; DBH = diameter at breast height; BL = clear bole length; H = mean height of tree; HD = height-to-diameter ratio; RGI = mean radial growth increment.

[b] Over bark values. Means in the same column followed by the same letters indicate no significant differences between these planting densities at $P < 0.05$ as determined by Duncan multiple range test. Values in the parentheses represent standard deviations.

fibers in each sample were measured. Vessel density (VD; per square millimeter) and vessel area (VA; percentage) at a magnification of ×100 were measured by the image processing software calibrated with a stage micrometer. The average number of vessels in 30 standard fields of observation frame under the microscope was considered as VD. In addition, ray cell density (RD; per square millimeter) and ray area (RA; percentage) were measured within a field (1 mm^2) in tangential sections (at a magnification of ×100). The ray cell features were measured with 50 readings in each sample block. The VA and RA were measured on the transverse sections. Using the mouse pointer, the ray cell areas were carefully traced manually and covered using the microscope image analysis software image editing command. The application of the automatic area identification procedure was not possible, because the pattern of the vessels and the rays in transverse section were irregular and, therefore, were difficult to separate from the others. The manually covered areas were then expressed as a proportion of vessel and ray tissue.

Statistical analysis

Duncan's post hoc test ([Duncan multiple range test] at the probability level of 95% [$P < 0.05$]) was used to detect differences between planting densities. The normality of collective data was tested for skewness, and a Shapiro-Wilk test was performed. Pearson's correlation coefficients between stand/tree features and wood anatomical characteristics were also determined to show their relationships. Multiple regression equations were formulated to predict wood anatomical characteristics using planting density and tree features as predictor variables. A stepwise procedure was used to establish the best predictor variables for the regression equations. The variance inflation factor (VIF) was used to identify multicollinearity of the predictor variables. The established models were evaluated based on the coefficient of determination (R^2) and level of significance (Ho 2006). Guilford's Rule of Thumb (1973) was used to explain the strength of correlations ($r < 0.2$, negligible relationship; $r = 0.2$ to 0.4, low relationship; $r =$ 0.4 to 0.7, moderate relationship; $r = 0.7$ to 0.9, high relationship; and $r > 0.9$, very high relationship).

Results

Effect of initial PD on tree features, WD, and wood anatomical characteristics

The average values of tree growth features from the different planting densities were tabulated in Table 1. DBH at PD I was different from DBH at the other three PDs. A significant effect of initial planting density on BL was also observed, with higher planting densities producing the taller trees. There were also significant planting density effects on both stem quality parameters, with HD increasing and RGI decreasing (Table 1).

The WD was 0.64 g/cm^3 at PD I, significantly higher than at the other three PDs (Table 2). Minimum to maximum average FL and FWT values varied from 5.3 to 22.1 percent. Although there was a decreasing tendency of these three characteristics from low to high planting densities, the analysis of variance results showed significant differences only between PD I and PDs II, III, and IV.

The VD ranged from 3.12/mm^2 in PD II to 4.10/mm^2 in PD IV. This indicated more vessels with higher planting densities (a 31.4% increase). The difference was significant only between PDs II and IV. RD increased toward higher planting densities (22.9%) with a significant difference only between PD I and the three other PDs ($P < 0.05$). No significant effects of initial planting density on VA and RA were observed (Table 2).

Relationships between tree features, WD, and wood anatomical properties

Pearson's correlation coefficients between tree features, WD, and wood anatomical characteristics in *H. brasiliensis* are presented in Table 3. In general, the tree growth features showed various degrees of correlations with WD and wood anatomical properties.

WD was dependent on all tree features and was negatively related to PD, BL, and HD (Table 3). There was good correlation between FL and PD followed by RGI and DBH. FWT was significantly and negatively related to PD and HD and was significantly and positively related to DBH and RGI. In terms of vessel features, only VD and BL were significantly and positively correlated. In contrast, VA as well as RA was not correlated with tree features. Surprisingly, RD showed significant negative correlations with DBH and RGI, but significant positive correlations with the others.

Empirical modeling WD and anatomical properties in relation to stand/tree features

The best models established by the stepwise procedure are depicted in Table 4. The models indicate the change (R^2 × 100) in variance described by the independent variables. WD was best predicted by PD, HD, and RGI, with an R^2 value of 0.466 (Model 1). With respect to the FL equation, PD was introduced in addition to BL, and the total amount of variation described was moderate ($R^2 = 0.141$, Model 2). In contrast, Model 3 ascribes approximately 40 percent of the total variation in FWT with PD and BL as predictor

Table 2.—*Mean values of wood density and anatomical properties from four planting densities of clone RRIM 2025 in* Hevea brasiliensis.[a]

Clone	PD (trees/ha)	WD (g/cm^3)	FL (μm)	FWT (μm)	VD (per mm^2)[b]	VA (%)	RD (per mm^2)	RA (%)
RRIM 2025	500	0.64 B (0.02)	1,340 B (232)	4.8 B (1.1)	3.62 AB (2.41)	10.40 A (4.98)	6.21 A (1.93)	13.32 A (3.73)
	1,000	0.54 A (0.02)	1,279 A (214)	4.1 A (0.8)	3.12 A (1.79)	10.19 A (4.33)	7.18 B (3.23)	13.42 A (5.41)
	1,500	0.52 A (0.03)	1,272 A (242)	4.0 A (0.8)	3.60 AB (1.84)	11.80 A (4.32)	7.39 B (3.00)	13.52 A (4.31)
	2,000	0.54 A (0.03)	1,276 A (244)	3.9 A (0.9)	4.10 B (2.98)	9.70 A (4.37)	7.63 B (2.11)	13.12 A (4.10)

[a] Means in the same column followed by the same letters indicate no significant differences between these planting densities at $P < 0.05$ as determined by Duncan multiple range test. Values in parentheses represent standard deviations. PD = planting density; WD = wood density; FL = fiber length; FWT = fiber wall thickness; VD = vessel density; VA = vessel area; RD = ray density; RA = ray area.

[b] High standard deviations in vessel density is related to no existing vessel in some fields under the microscope.

Table 3.—Correlation coefficients between tree features, wood density, and wood anatomical properties with planting densities of H. brasiliensis.[a]

Variable	WD	FL	FWT	VD	VA	RD	RA
PD	−0.639**	−0.289**	−0.355**	0.176	−0.022	0.266**	−0.029
DBH	0.512**	0.193*	0.271**	0.088	0.042	−0.202*	0.063
BL	−0.408**	−0.048	−0.134	0.189*	−0.006	0.195*	−0.048
HD	−0.488**	−0.139	−0.196*	0.057	−0.062	0.203*	−0.055
RGI	0.511**	0.269**	0.197*	0.089	0.043	−0.199*	0.066

[a] WD = wood density; FL = fiber length; FWT = fiber wall thickness; VD = vessel density; VA = vessel area; RD = ray density; RA = ray area; PD = planting density; DBH = diameter at breast height; BL = bole length; HD = height-to-diameter ratio; RGI = mean annual growth increment; ** = correlation is significant at the 0.01 level; * = correlation is significant at 0.05 level.

Table 4.—Models describing wood density and wood anatomical properties with respect to stand/tree features in Hevea brasiliensis.[a]

			Parameter estimation			
Model	DV	IV	Regress. Coeff.	SE	VIF	R^2
1	WD	Intercept	0.443	0.057		
		PD	−6.42E−05	0		
		HD	0.124	0.05	3.548	0.466
		RGI	0.07	0.02		
2	FL	Intercept	1,228.418	43.77		
		PD	−0.076	0.018	2.16	0.141
		BL	0.184	0.065		
3	FWT	Intercept	3.93	0.473		
		PD	−0.001	0	2.16	0.401
		BL	0.002	0.001		
4	VD	Intercept	0.131	1.194		
		BL	0.002	0.001	1.224	0.071
		RGI	0.783	0.372		
5	VA	NA	NA	NA	NA	NA
6	RD	Intercept	5.983	0.411		
		PD	0.001	0	1	0.071
7	RA	NA	NA	NA	NA	NA

[a] DV = dependent variables; IV = independent variables; Regress. Coeff. = regression coefficient; SE = standard error; VIF = variance inflation factor; WD = wood density; PD = planting density; HD = height-to-diameter ratio; RGI = mean annual growth increment; FL = fiber length; BL = bole length; FWT = fiber wall thickness; VD = vessel density; VA = vessel area; NA = not applicable; RD = ray density; RA = ray area.

variables. VD was best predicted by BL and RGI (Model 4) that only about 7 percent of the variation in VD was explained by the variables included in this parameter's estimation. In terms of RD, the total amount of variation explained was similar to that of the VD model ($R^2 = 0.071$), but only one predictor (PD) entered the equation.

Unfortunately, a model for VA and RA could not be determined, and none of the stand/tree features were chosen in the stepwise procedure (Models 5 and 7). Although some stand/tree features were selected for the model, the variable DBH never entered the model because of high multicollinearity with HD ($r \geq 0.9$; Ho 2006). According to the R^2 values, the RD and VD models are not sufficient to explain the relationships with tree features.

Discussion

Effect of initial PD on tree growth features, WD, and wood anatomical properties

The significant effect of initial planting density on tree growth, stand yield, and wood quality has been documented

(Zobel and Van Buijtenen 1989, Jiang et al. 2007). The present study apparently shows different degrees of effects of initial planting densities on tree growth features, wood density, and wood anatomical properties in *H. brasiliensis*. In particular, trees grew faster at the lower stand density in terms of radial growth (DBH). This is attributed to the effect of wider spacing on tree growth. The widely spaced trees tend to effectively capture more sunlight and absorb sufficient moisture and nutrients for growth. Eventually, this increases the growth rate (Macdonald and Hubert 2002, Naji and Sahri 2012). This can also be related to the larger crown size at the lower planting density (Jiang et al. 2007). Additionally, a lower HD was observed at the lower planting density, indicating inferior stem quality from this density compared with those from higher planting densities. HD, which is highly associated to silvicultural practices, can be an important feature to control wood properties (Kijidani et al. 2010).

The initial planting density significantly influenced wood density only in PD I. This result was in agreement with the previous studies on *Acacia* (Zobel and Van Buijtenen 1989) and poplar (*Populus xiaohei*) (Jiang et al. 2007), where wood density decreased with increasing planting density. However, Lim and Fujiwara (1997) reported that wood density in rubberwood increased as planting density increased. This incongruity may be related to differences in species, site, or environmental conditions. According to the generalization made by Zobel and Van Buijtenen (1989), the initial planting density usually used in practice has little effect on wood density.

Fiber length is one of the most important features affecting the quality of pulp and paper, and lengthy fibers enhance the strength properties of the paper (Macdonald and Hubert 2002). This study pointed out that fiber length in crowded planting densities of *H. brasiliensis* was hardly affected by the number of trees per hectare. Similar results were reported for some poplar clones (Koubaa et al. 1998, Jiang et al. 2007), where fiber length was not affected by tree spacing. Usually, normal initial spacing was documented to have little effect on fiber length (Zobel and Van Buijtenen 1989). This finding is in contrast with observations in some coniferous species that showed wider spacings resulted in shorter fibers (Watson et al. 2003). The variation in fiber length with initial planting density is a controversial issue. Generally, fiber length is controlled by inheritance (Zobel and Van Buijtenen 1989). In this study, there was no genetic variation, and therefore the most acceptable reason for any changes may be related to environmental factors resulting from the distances between trees. However, no significant changes were observed at high planting densities (Table 2). Consequently, it may be said that variations at the low planting density were more visible than at high planting densities.

The average wall thickness in this study was within the range reported for rubberwood (Roslan 1998, Norul Izani and Sahri 2008, Teoh et al. 2011). The evidence from the literature and from the present study suggests that rubber clones are suitable as forest plantation species, and the range of their fiber features is comparable to or better than some popular tropical hardwoods such as *Acacia* (Alfred 2007).

No significant differences in WD, FL, and FWT between the three higher planting densities could be an important achievement in terms of yield and use of wood resources in forest product industries like pulp and papers. In the extremely high PD (2,000 trees per ha), the average wood volume per hectare was significantly higher (149.1 m^3/ha compared with 66.9 m^3/ha) than in the moderate PD (1,000 trees per ha; Naji and Sahri 2012). This shows that the planting strategy can be highly focused on extremely high planting density because the importance of wood density and fiber features can be maintained.

In spite of numerous studies on relationships between planting density and fiber morphology, only a few studies highlight vessel sizes, ray cell features, and their variability. In hardwoods, vessel features (area and size) influence the paper making process. In species with high vessel percentage, the pulping liquor can easily penetrate into wood, and the increased bulk can result in lowered quality of paper surface characteristics, particularly its printing ability and leaving some ink-free spots on the printed page (Leal et al. 2003).

The mean VD for rubberwood is between 2 and 4 per mm^2. However, this feature can differ with age (Roslan 1998). The VD varies with planting density and maturity of the wood. Usually, the number of vessels in juvenile wood is more than in mature wood. This is supported by the high physiological activities (particularly water transportation) in younger trees and likewise, younger trees have narrower vessel diameters than older trees (Lev-Yadun and Aloni 1995, Sagaya 1996, Syeed Saifulazry 2007).

Cellular composition and tissue percentage (VA and RA) change with growth rate, with distance from the pith, and with thickening of the stem (Iqbal and Ghousevat 1987, Lev-Yadun and Aloni 1995), but usually no generalization can be made (Rao et al. 2003). For example, no notable effect was observed in *Eucalypt* species, while a decrease and a gradual increase in some different species were reported (synthesized from Leal et al. 2003). In this study, the initial planting density showed no significant impact on variability of VA and RA. We did not find any descriptions of ray feature variations with initial planting density in rubberwood, and hence to our knowledge, this report is the first report on the effect of initial planting densities on vessel and ray cell features.

The ray number is an important element that affects dimension stability (especially radial shrinkage) and Young's modules of the wood (Rahman et al. 2005). In the case of RD in this study, the significant effect was evident only in PD I. Like most other anatomical features, these surprising results suggest that the response of wood anatomical features to initial planting density is more visible at the low PD (500 trees per ha). Therefore, with respect to wood quality, the wood formed at the low PD is characterized by heavier wood density, longer fiber length, thicker fiber cell wall, and lower ray density.

Relationships between tree growth features, WD, and wood anatomical properties

The correlation analysis showed that there were different degrees of correlation between tree growth features, wood density, and anatomical properties in this species (Table 3). The magnitude of relationship between wood density and tree growth features is a key factor because it always relates to other wood properties (Lei et al. 1997). A weak correlation would show that faster growing trees have little effect on wood density or other traits. Usually the correlation between tree growth features and wood density in diffuse-porous species is weak (Weber and Sotelo Montes

2010). In the present study, the magnitude of correlations between tree growth features and wood density were moderate ($0.4 < r < 0.7$). Negative correlations in PD, BL, and HD showed that with increasing these values, the WD decreased, i.e., WD was higher in the stand at the low PD, with shorter BL and with smaller HD. Consequently, the timber-tree improvement programs must focus on low planting densities (Zobel and Jett 1995).

The FL was negatively related to PD and positively related to DBH and RGI. These results are in good agreement with Jiang et al. (2007), with a longer FL and a larger DBH at a lower PD. It was noted that faster growing species have shorter FL (Zobel and Van Buijtenen 1989). The strength of the relationship for PD with RGI was low and with DBH was negligible. Consequently, in view of this magnitude, the FL cannot be considered a reliable parameter to characterize tree growth conditions. However, FWT was negatively correlated with PD and HD characteristics and positively correlated with DBH and RGI. The results indicated that FWT of the disk from a low planting density was thicker in general than the FWT of the disk from a high planting density.

The anatomical features VD, VA, and RA showed very poor correlation with stand/tree features. An exception with a significant and positive relationship was observed between VD and BL with negligible strength ($r = 0.189$). This indicates that stand/tree features did not impact these properties. It is interesting to note that RD was significantly related to stand/tree features, but with a low magnitude of relationship for all characteristics. However, RD exhibited negative relationships with DBH and RGI. Specifically, with increasing DBH the number of rays per square millimeter was significantly decreased. The reduced number of rays in larger trees could be attributed to the higher incidence of FL and FWT, which resulted in higher WD. The low correlation between anatomical properties and tree growth features may be assigned to the fact that the competition between trees was newly started. The full impact of the competition may appear well when the trees' crowns reach each other.

Modeling WD and anatomical properties in relation to stand/tree features

The models showed that when using wood density and anatomical properties, the variance in the change ($R^2 \times 100$) can be explained by independent variables (stand/tree features). The regression analysis showed that the selected stand/tree features, i.e., PD, HD, and RGI, could only describe 47 percent ($R^2 = 0.466$) of total variation in WD (Model 1). It should be emphasized that both HD and RGI are important stem quality parameters. There was a low correlation between the explanatory variables as indicated by the VIF values. Previous studies on poplar and red alder (*Alnus rubra*) have also shown no relationships between WD and growth rate (Lei et al. 1997, Jiang et al. 2007).

FL was only weakly described by the joint effect of PD and BL ($R^2 = 0.141$; Table 4 and Model 2). Therefore, FL was not highly influenced by stand/tree features. Similar results were reported for poplar and red alder (Lei et al. 1997, Jiang et al. 2007). Among all the anatomical properties, FWT was best predicted by the explanatory variables PD and BL, which accounted for 40 percent of the total variation (Model 3). However, the models for vessel and ray cell features performed poorly (Table 4). The failure in good modeling for stand/tree features can be partly related to the low variation in these values from the different planting densities (Table 2). The average VIF for all models was in the safe range, and it was confirmed that collinearity was not a problem with the data.

In the predictions of vessel and ray cell features, VD was introduced with BL and RGI, while RD was only described by PD. The total amount of variation was smaller than that predicted by fiber features (Models 4 and 6). In particular, these two explanatory variables were the best for prediction of VD and RD, and they accounted for 7 percent of the total variation. Models 5 and 7 did not effectively explain the relationship of wood tissue parameters with stand/tree features, indicating that more effective explanatory variables need to be included into these models. Similar results in VA were noted in red alder (Lei et al. 1997). Small variations in vessel and ray cell features with growth rate and tree features indicate little effect on wood characteristics, i.e., wood density, machinability, strength properties, or pulp yield. Hence, no significant changes in ray area indicate any significant effect on wood drying rate and dimension stability shrinkage, and this would not slow the pulping process.

Additionally, these models confirm that initial planting density emerged as an active parameter for prediction of the studied features. It accounted for much of the variation in the features. Moreover, planting density can change the environmental conditions within the stand. Consequently, initial planting density can be manipulated to influence tree growth and eventually affect wood production and quality.

Conclusions

Recent studies have not provided comprehensive evidence quantifying the impact of *H. brasiliensis* stand/tree features on wood density and anatomical properties. The current findings have given an account of various effects of stand/tree features on the wood density, fiber, vessel, and ray cell features.

The initial planting density had a strong effect on DBH with the low planting density. However, BL showed high values in the higher planting densities. It was evident that lower planting density produced trees with larger DBH and lower HD. The significant effect of initial planting density on WD, FL, FWT, and RD was more visible in the low PD than in the higher PDs. With regard to VD, the low PD showed a slight decrease, which was significantly different from the extremely high PD. Further, no significant effect of planting density on VA and RA of individual stands was found.

In *H. brasiliensis,* high planting density strategies are achievable to increase wood biomass while keeping these features at acceptable values suitable for pulp and paper management purposes. In contrast, however, the aim of timber production should involve strategies for low-density stands in order to produce wood with more desirable high mechanical properties.

In terms of models to describe the features, wood density followed by fiber wall thickness was the best variable to predict variations in the stand and trees. The other variables performed poorly in the models. Hence, information on wood properties from the stand/trees before harvesting is limited. A controversial issue that needs to be acknowledged is related to the paucity of sampling. A larger sample size may be required to enhance the efficiency of these models for use in practice.

Taken together, initial planting density should be planned to design the final interested products. The intraclonal variations in *H. brasiliensis* wood density and anatomical wood properties offer possibilities for selecting superior initial planting density for experimental plantings at different locations.

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